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FRENCH LIMITED SITE
CROSBY, TEXAS

HYDROGEOLOGIC CHARACTERIZATION REPORT

Submitted To:

U. S Environmental Protection Agency

and

The Texas Water Commission

Submitted By:

Applied Hydrology Associates, Inc.
Denver, Colorado

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EXECUTIVE SUMMARY

The French Limited site is located on 22.85 acres south of U.S. Highway 90 and north of Gulf Pumping Station Loop Road approximately one mile southwest of Crosby, Texas and one-half mile west of Barrett, Texas. The Riverdale Subdivision lies to the southwest of the site. The site consists mainly of a 7.3-acre unlined lagoon, formally a sand and gravel pit, which was used between 1966 and 1972 for the disposal of a variety of petrochemical and wood preservative residues. Disposal of the residues was performed by French Limited under a temporary permit issued by the Texas Water Quality Board. The permit was revoked and French Limited was ordered to cease operations in 1973 after extensive public hearings and legal proceedings The residues have formed a sludge layer at the bottom of the lagoon containing elevated concentrations of certain organic constituents and metals. In 1982, the site was put on the National Priorities List (NPL) and designated for remediation action under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) also known as "Superfund."

Lockwood, Andrews & Newnam, Inc (LAN) performed remedial investigation studies from 1983 to 1985 under contract to the Texas Department of Water Resources and in cooperation with the Region VI office of the U.S Environmental Protection Agency (EPA). The French Limited Task Group was formed in late 1983 by potentially responsible parties associated with the site. A Remedial Investigation and Feasibility Study (RI/FS) was completed for the Task Group by Resource Engineering, Inc. (REI) and accepted by EPA in 1986. Pilot biodegradation tests on the lagoon sludge were initiated on site in 1987 and continued until late 1988. A Record Of Decision (ROD) was issued in 1987 by EPA allowing biodegradation as a remedial technology.

The RI/FS reports identified groundwater contamination in the alluvial sediments below and adjacent to the French Limited Lagoon. Remediation of the alluvial groundwater is part of the overall site clean-up plan. More detailed information about the hydrogeologic characteristics of the alluvium was required in order to more adequately assess groundwater contaminant transport and design appropriate groundwater remediation measures Accordingly, in addition to ongoing monitoring of groundwater, a number of supplemental studies have been performed at the site since 1987. These have included a soil vapor survey completed by ENSR in 1988 and aquifer testing of the alluvial sediments performed in 1988 by Applied Hydrology Associates, Inc. (AHA) in cooperation with ENSR.

The report which follows has been prepared to consolidate the data from all previous investigations in order to characterize the site geology and hydrology. This characterization is directed at evaluating the pathways, rates and mechanisms of contaminant migration and providing a fundamental understanding of the site hydrogeology and aquifer characteristics needed to design and assess groundwater remediation alternatives.

HYDROGEOLOGIC SETTING

Geologic interpretations have been developed using primarily cone penetrometer test data and geophysical logs of bore holes. Based on these data, it has been determined that the upper stratigraphy in the vicinity of the French Limited site may be divided into three zones: the lower silty sand zone, the middle clayey zone and the upper alluvial zone.

Lower Silty Sand Zone

The lower silty sand zone is comprised of poorly consolidated water-bearing silty sand, sandy silt, and silty clay. The top of the zone occurs at a depth of approximately 109 to 137 feet below ground surface. The top of the zone is defined by a silty sand stratum which is apparently continuous about the French Limited site and environs and ranges from six to 14 feet in thickness. The lower silty sand zone may represent a sandy zone within the Beaumont Formation or the upper part of the Montgomery Formation which underlies the Beaumont.

The lower silty sand zone is characterized as a confined aquifer having variable geologic and hydrogeologic properties in the area investigated. Results of a seven-day aquifer test performed during the 1986 supplemental field investigations indicated that the unit is hydraulically continuous at least within 1000 feet of the test well located near the southwest corner of the French Limited Lagoon. The average hydraulic conductivity of the zone measured during this seven-day test ranges from a high value of $4x10^{-3}$ centimeters per second (cm/sec) to a low of $1x10^{-3}$ cm/sec.

Potentiometric variation within the lower silty sand zone indicates a general eastward hydraulic gradient of about 0 001 foot per foot (ft/ft) (6 3 ft/mile). The direction of the potentiometric gradient is thought to result from pumping of water supply wells near the town of Barrett.

Middle Clayey Zone

The middle clayey zone consists of 61 to 93 feet of thinly interbedded silty clays, clayey silts, and silty sandy clays of the Beaumont Formation. The top of the middle clayey zone occurs at a depth of about 43 to 55 feet below ground surface. The clays of the middle clayey zone are characteristically reddish-brown or blue-grey with reddish mottling, are blocky in texture and contain slickensides. The middle clayey zone is an aquitard which isolates the groundwater of the upper alluvial zone from the lower silty sand zone.

The middle clayey zone is saturated, but, due to its clayey nature, it does not yield water easily to wells and tends to restrict the transmission of groundwater to adjacent aquifers. Well and piezometer data indicate a dramatic drop in potentiometric head through the middle clayey zone. This drop in head is equivalent to an average vertical hydraulic gradient of about 1.0 ft/ft. This supports the interpretation that the middle clayey zone provides substantial resistance to vertical groundwater flow.

Consolidation tests from cores indicate laboratory hydraulic conductivity values for clays of the middle clayey zone in the range of 1.23×10^{-9} to 2.05×10^{-10} cm/sec. Slug tests on piezometers completed within clay strata of this zone indicate field hydraulic conductivities in the range of 10^{-6} to 10^{-7} cm/sec. A field estimate of the vertical hydraulic conductivity of the lower portion of the middle clayey zone was determined from the hydraulic response of the middle clayey zone to pumping the lower silty sand zone. The average vertical hydraulic conductivity for this unit is calculated to be about 7×10^{-7} cm/sec. This value is considered to be conservatively high because a conservatively high value of specific storage was used to determine the hydraulic conductivity.

Upper Alluvial Zone

The upper alluvial zone consists of poorly consolidated sands, silty sands, gravels, and clay strata deposited by the San Jacinto River in a meander belt that is now abandoned. The upper alluvial zone is up to approximately 55 feet thick and thins out to zero thickness at the margins of the abandoned meander belt to the south and east of the lagoon. The geologic information from a number of bore holes and cone penetrometer tests indicates a high degree of vertical and lateral grain-size variation within the upper alluvial zone which is typical of alluvial deposits. However, the geologic interpretation suggests that the unit may be subdivided into four distinct strata which have appreciable lateral extent.

The upper alluvial zone is mostly saturated and yields water to wells The zone is considered as a single hydrogeologic unit due to the apparent good hydraulic communication within the unit. This is suggested by the similarity of potentiometric levels within the upper alluvial zone and the rapid response of monitoring wells completed at the base of the zone to influences affecting the near-surface water table Spacial variation in hydraulic conductivities can generally be related to variation in grain size. The groundwater in the upper alluvial zone is unconfined but may display confined characteristics locally where significant clay lenses exist within the zone. Low permeability clay and silt strata within the zone tend to locally restrict vertical ground water movement.

The potentiometric surface in the vicinity of the French Limited Lagoon is quite flat although it appears that a groundwater divide may exist to the north of the French Limited Lagoon near U.S. Highway 90. South of this groundwater divide the potentiometric surface slopes at an average gradient of about 0.001 ft/ft toward the unnamed stream that is tributary to Rickett Lake. Groundwater from the topographically higher area upon which the Riverdale Subdivision is built flows easterly at a gradient of about 0.01 to 0.03 ft/ft. Groundwater from the topographically higher areas to the east flow westerly at a gradient of about 0.002 ft/ft. The upper alluvial zone groundwater system is recharged directly by precipitation and from surface runoff and ponds particularly in the winter and spring quarters.

The upper alluvial zone between the French Limited Lagoon and the Riverdale Subdivision appears to have a relatively low average hydraulic conductivity based on the results of slug tests and the very low well yields in this area. Geologic information indicates very little sand within the tested intervals of these low-yielding wells. This supports the interpretation that the upper alluvial zone does have a low permeability in this area and that the low values of hydraulic conductivity calculated are not the result of poor well completions or test methodology.

A more transmissive zone in the upper alluvial zone appears to exist to the southwest of the French Limited Lagoon. This zone is localized and bounded by low transmissivity areas to the northeast and the southwest. The estimated transmissivity for this area ranges from 2900 to 8400 gpd/ft based on three well tests. The high transmissivity area may be associated with a channel sand or point bar deposit in the upper alluvial zone. The trend of the high transmissive area appears to be northwest-southeast although the lateral extent is undefined. The relatively high hydraulic conductivities calculated from aquifer tests in this area are consistent with the low clay content (five to 13 percent) and relatively high sand content (18 to 33 percent) at these sites

The results of longer term aquifer tests of wells to the south of the French Limited Lagoon generally indicate values of transmissivity in the range from 600 to 1400 gpd/ft. Transmissivity values appear to decrease to between 100 and 800 gpd/ft toward the southwest corner of the French Limited Lagoon The relatively low average hydraulic conductivity values measured in this localized area is consistent with the high clay content noted in the tested intervals (37 to 88 percent) although the sand content is reasonably high

Isopleths of the average hydraulic conductivity in the upper alluvial zone developed from the results of pumping tests compare favorably with soil vapor survey information. Areas of higher average hydraulic conductivity appear to correlate with higher volatile organic concentrations in soil vapor suggesting that these zones constitute the primary migration routes for contaminated groundwater.

Groundwater flow rates may be estimated on the basis of standard flow equations and reasonable ranges of hydraulic conductivity, hydraulic gradient and effective porosity within the zone of interest. Flow rates to the south of the French Limited Lagoon are of most interest as they are directly related to potential constituent migration from the lagoon. Average hydraulic conductivities within the upper alluvial zone are probably more representative for calculating groundwater flow rates due to the limited continuity of individual units within the zone. The average hydraulic conductivity of upper alluvial zone sediments to the south of the lagoon is in the range 8×10^{-4} to 2×10^{-3} cm/sec. Maximum measured hydraulic gradients to the south of the lagoon range from 0.006 to 0.008. The effective porosity within granular materials is probably within the range 0.1 to 0.3. Average groundwater flow velocities are calculated to be in the range 50 to 100 feet per year. On this basis, groundwater movement over the past 20 years is likely to have been between 1000 and 2000 feet to the south of the French Limited Lagoon.

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CONTAMINANT MIGRATION IN THE UPPER ALLUVIAL ZONE

The distribution of constituents within the shallow groundwater of the site is influenced primarily by the chemical properties of the constituent, the geometry and characteristics of the source area (the lagoon), the rate and direction of groundwater flow, and the hydrogeologic characteristics of the shallow subsurface materials. Migration of constituents appears to be restricted to the upper alluvial zone and the upper few feet of the underlying middle clayey zone.

Organic constituents occur in the groundwater of the upper alluvial zone. Generally, the highest concentrations of dissolved solutes occur around the margins of the French Limited Lagoon. Certain organic constituents found in the sludges, such as PCBs, have not been detected in any groundwater samples due to the strong tendency of these chemicals to bind to solid matrices. Concentrations tend to decrease downgradient from the lagoon in approximate accordance with the mobility of the various constituents. Most semi-volatile organic constituents, with the notable exception of napthalene, are not detectable in monitoring wells 150 to 200 feet downgradient from the lagoon. This reflects the generally low mobility of these constituents in groundwater due primarily to adsorption on the aquifer materials.

Volatile organics such as benzene and vinyl chloride that are mobile in groundwater tend to be found in measurable concentrations at some distance from the source area. Benzene and vinyl chloride distribution in groundwater show essentially the same pattern of migration, but vinyl chloride shows more temporal variability in individual wells. Due to their relatively high solubilities, mobilities and carcinogenic properties, both benzene and vinyl chloride have been identified as indicator parameters to be monitored in groundwater. In this report, benzene has been selected as reasonably representative of mobile organic compounds in groundwater in the upper alluvial zone and has been used to illustrate the spatial and temporal variation in concentration of these constituents in the vicinity of the site.

The geometry and nature of the source area tends to be the dominant control of dissolved organic concentrations in groundwater near the margins of the lagoon. The French Limited Lagoon sludges contain high concentrations of volatile organic constituents. Desorption of these constituents from the sludges tends to be difficult due to the high organic carbon content of the sludges and the high affinity of volatile organics for organic substrates This would partially explain the very low organic concentrations noted in samples of the lagoon water.

Core samples taken below the lagoon sludge layer indicate that oily liquids, presumably from disposal operations, have infiltrated directly into the underlying alluvial sediments. These sediments contain relatively low organic carbon contents (two to six percent) and should have less tendency to chemically bind organic constituents. It is therefore likely that the sediments directly below the lagoon, containing relatively high concentrations of organics, provide the major source for these constituents to enter the groundwater of the upper alluvial zone.

The wide range of organic content within the sludge and underlying sediments is reflected in the variability of organic concentrations in groundwater samples in close proximity to the lagoon. Groundwater concentrations probably vary both laterally and vertically in the stratified upper alluvial deposits near the source area as dispersive influences are limited. In areas downgradient from the lagoon, dispersion and other mixing processes will tend to reduce the vertical and lateral variability in groundwater concentration at any given location.

Water samples from monitoring wells screened through several feet of the alluvium essentially represent a composite of groundwater drawn from the stratified units at that location. The concentrations in groundwater within the individual strata may differ considerably, particularly close to the lagoon source area. Consequently, composite groundwater concentration sampled from a monitoring well tapping these stratified units can also vary between sampling events despite all reasonable efforts to maintain consistency in sampling protocol. The temporal variation would tend to be most apparent in wells close to the lagoon. For example, benzene concentrations tend to range widely both areally and temporally close to the lagoon, but are fairly consistent downgradient from the lagoon Some of the temporal variations in wells close to the western part of the lagoon are attributable to operations during the biodegradation demonstration.

The distribution of mobile organic constituents in upper alluvial zone groundwater away from the immediate vicinity of the lagoon generally follows groundwater flow directions as determined from potentiometric data The potentiometric data indicate that the general flow direction is to the south from the lagoon. The water quality data and the soil vapor survey support this interpretation.

The results of extensive groundwater quality monitoring between the French Limited Lagoon and the Riverdale Subdivision, and in the Riverdale Subdivision itself, show no evidence of organic contamination in subdivision wells that can be attributed to groundwater transport from the French Limited site. Potentiometric data indicate gradients from the Riverdale Subdivision toward the potentiometric and topographic low areas south of the French Limited Lagoon. Furthermore, none of the mobile organic constituents that are typical of groundwater affected by the French Limited Lagoon, such as benzene, trichloroethane and vinyl chloride, are detectable in the Riverdale Subdivision wells. The occurrence of two phthalate compounds (bis(2-ethylhexyl) phthalate and di-n-octyl phthalate) in four of the Riverdale Subdivision wells is interpreted as being due to PVC pipe and well casing as both phthalates are used as plasticizers in the production of PVC products. The phthalate compounds also have extremely low mobility in groundwater due to their high hydrophobic characteristics. For example, bis(2-ethylhexyl) phthalate is typically about one million times less mobile than benzene in groundwater.

The western extent of detectable organic migration in the upper alluvial zone appears to be east of the line of wells completed between the old Harris County Landfill and the Riverdale Subdivision. Samples from all these wells have not shown any detectable volatile organic constituents in numerous samplings during 1988. Samples from a well screened within the disposal materials of the old Harris County landfill show very low concentrations of benzene (three and six parts per billion). These low levels of benzene are most likely attributable to leaching of landfill materials.

The extent of organic migration in the upper alluvial zone is not sufficiently well defined to the north, east, and south of the lagoon for remedial design purposes due to a sparse distribution of monitoring wells in these areas. Sampling of five shallow monitoring wells located to the north of US Highway 90 did not indicate groundwater migration of organic constituents from the French Limited lagoon in this area. This is consistent with the general indication of groundwater flow below to the lagoon in a southward direction. To the east of the lagoon, the extent of groundwater contamination in the upper alluvial zone is constrained by the eastern margin of the alluvial deposits and the consistent indication of westerly groundwater flow gradients in this area.

Measurable concentrations of organic compounds are consistently found in monitoring wells located some 200 feet south of the lagoon. A monitoring well located approximately 700 feet south of the lagoon showed no evidence of volatile organics based on samples taken in 1983. A sample taken in 1984 from a well located just to the south of the South Pond and about 600 feet south of the French Limited Lagoon showed detectable concentrations of chloroform and 1,2 dichloroethane but no other volatile organics. Two other monitoring wells completed in different intervals within the upper alluvial zone at the same location did not show any detectable organic concentrations. It is possible that organic detected in the one well sample south of the South Pond does not represent groundwater migration from the French Limited Lagoon.

Generally, the areas of measurable volatile organics in soil vapor correlate well with shallow groundwater quality data from monitoring wells. It appears that fairly significant volatile concentrations in shallow groundwater, corresponding to at least 100 parts per billion benzene, are required to generate measurable soil vapor concentrations in the overlying unsaturated zone. The soil vapor survey indicated elevated volatile organic concentrations east of the Riverdale Subdivision where water quality results show no detectable volatiles in groundwater. The soil vapor in this area does not appear to be related to groundwater quality and is more likely influenced by historic surface water flows along a drainage ditch in this location.

The distribution of benzene in the upper alluvial zone groundwater would suggest a migration of this constituent of at least 500 feet to the south of the French Limited Lagoon. Assuming that organic constituents first entered in the alluvial groundwater at the start of disposal operations at the French Limited site in 1966, the average migration rate to the south is about 20 to 25 feet per year. Groundwater flow rates to the south of the lagoon are probably in the range 50 to 100 feet per year and would indicate advection distances over the past 20 years of 1000 to 2000 feet. On this basis, the benzene migration distances appear to be 25 to 50 percent of that which would occur as a result of advection.

The lesser constituent migration rates compared with advective groundwater flow rates is reasonable as retardation and natural degradation processes will tend to attenuate the rate of constituent transport in groundwater. The stratified nature of the upper alluvial zone sediments and the limited continuity of individual units will enhance retardation processes. As a result, solute migration rates of mobile constituents will tend to approach advection rates based on average permeabilities rather than the highest permeability units.

IMPLICATIONS FOR GROUNDWATER REMEDIAL ACTION

The hydrogeologic characterization of the site supports groundwater withdrawal and treatment as a basic, viable remedial action for the upper alluvial zone at the French Limited site. In specific areas, this basic remedial option may be complimented by additional active measures and by natural processes in order to achieve clean-up objectives for the groundwater in an environmentally acceptable manner and within a reasonable time-frame. The characterization serves as a basis for design of the groundwater withdrawal system; highlights conditions that will influence clean-up efficiency; and identifies a few areas of additional data requirements to refine the design.

The groundwater remedial system should address two basic areas to control contamination in the upper alluvial zone associated with the site -- near-source control and migration control. Near-source control refers to remedial activities associated with groundwater and aquifer materials below, and in the immediate vicinity of, the French Limited Lagoon. Migration control refers to remedial activities associated primarily with affected groundwater that has migrated beyond the site boundaries.

The near-source control area may be considered to lie within 200 feet of the lagoon margin and north of Gulf Pump Road. Dissolved benzene concentrations in the groundwater typically range from 2000 to 5000 ug/l in this area In addition to the relatively mobile volatile and semi-volatile organic constituents, less-mobile organic and inorganic constituents are present.

The existing contamination in the groundwater and aquifer materials in the upper alluvial zone of the near-source area will be remedied primarily by groundwater withdrawal and treatment. This system will also remedy any additional organic releases into the upper alluvial zone resulting from biodegradation remedial activities. Withdrawal of groundwater in the vicinity of the lagoon will locally reverse the hydraulic gradient thus inducing groundwater flow back towards the lagoon. This will tend to draw back contaminated groundwater that has migrated away from the lagoon and prevent any further migration of contaminated groundwater. Removal of organic constituents from the aquifer materials will be accomplished indirectly by reducing concentrations in the groundwater and thus inducing constituents to desorb from the aquifer materials.

The migration control area may be considered to approximately coincide with the area south of Gulf Pump Road which has benzene concentrations in the groundwater in excess of 5 ug/l. Concentrations of dissolved benzene in this area range from 5 to 2000 ug/l. The dissolved organic constituents in the groundwater of the upper alluvial zone in the migration area are relatively mobile volatile and semi-volatile compounds. Considering the

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type of constituents involved, a basic groundwater withdrawal system should be an efficient method of groundwater remediation in this area.

The progress of the groundwater clean-up will be tracked by routine monitoring of groundwater quality. This monitoring will be used to assess whether enhancement of the basic groundwater withdrawal scheme is necessary in order to meet clean-up time frames. Enhancement options that may be considered include reinjection of clean water to increase the rate of groundwater movement towards withdrawal wells, in-situ bioremediation, vacuum extraction, and alkali-polymer injection

1.0 INTRODUCTION

The French Limited site is located on 22.85 acres south of U.S. Highway 90 and north of Gulf Pumping Station Loop Road approximately one mile southwest of Crosby, Texas and one-half mile west of Barrett, Texas (Figure 1-1). The Riverdale Subdivision, with a population of about 100, lies to the southwest of the site (Plate 1). East of the Riverdale Subdivision and south of the site, Harris County operated a sanitary landfill in the 1960's on an 18 5-acre site (Plate 1). This landfill is no longer active. The remaining areas surrounding the site are largely undeveloped with numerous abandoned sand pits and low-lying swampy areas.

The French Limited site consists mainly of a 7.3-acre unlined lagoon, formally a sand and gravel pit, which was used between 1966 and 1972 for the disposal of a variety of petrochemical and wood preservative residues. Disposal of the residues was performed by French Limited under a temporary permit issued by the Texas Water Quality Board. The permit was revoked and French Limited was ordered to cease operations in 1973 after extensive public hearings and legal proceedings. The residues have formed a sludge layer at the bottom of the lagoon containing elevated concentrations of certain organic constituents and metals. In 1982, the site was put on the National Priorities List and designated for remediation action under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) also known as "Superfund "

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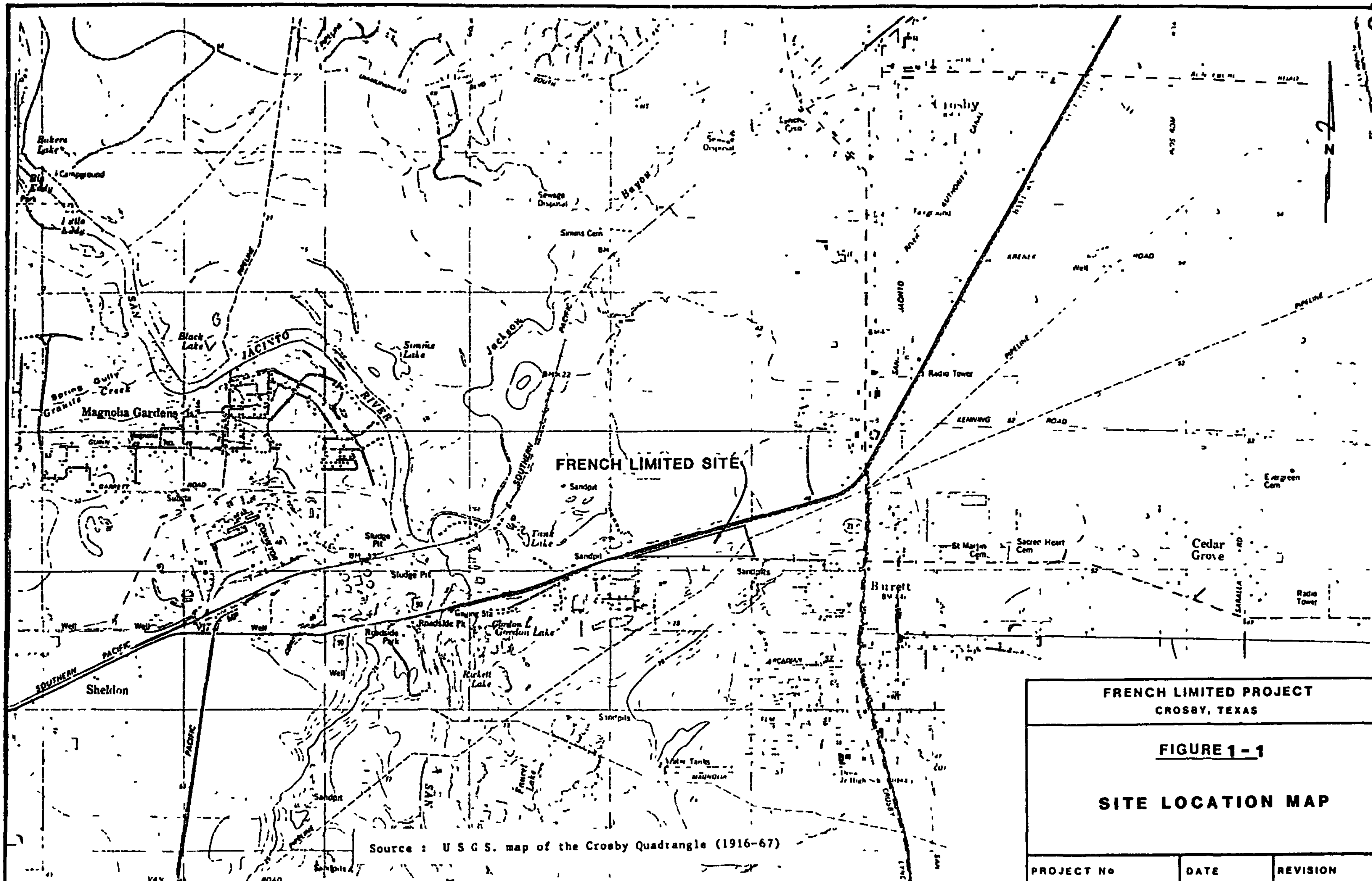
The RI/FS reports identified groundwater contamination in the upper alluvial sediments below and adjacent to the French Limited Lagoon. Remediation of the upper alluvial groundwater zone is part of the overall site clean-up plan. More detailed information about the upper alluvial zone hydrogeologic characteristics was required in order to more adequately assess groundwater contaminant transport and design appropriate groundwater remediation measures. Accordingly, in addition to ongoing monitoring of groundwater, a number of supplemental studies have been performed at the site since 1987. These have included a soil vapor survey completed by ENSR in 1988 and aquifer testing of the upper alluvial zone performed in 1988 by Applied Hydrology Associates, Inc. (AHA) in cooperation with ENSR.



FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 1 - 1

SITE LOCATION MAP

PROJECT No	DATE	REVISION

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER CO

1.1 OBJECTIVES AND SCOPE

The purpose of this report is to bring together the considerable volume of information pertaining to the hydrogeology of the site that has been collected since the beginning of investigations in 1981 which led the French Limited site being placed on the National Priorities List. In particular, the focus of this report is to characterize the site geology and hydrology in a manner which identifies the hydrogeologic features which control the pathways, rates and mechanisms of contaminant migration away from the French Limited Lagoon. To this end, topographic information, subsurface boring information, water level data, aquifer test data, and some chemical analyses data will be presented.

1.2 DATA SOURCES

Remedial investigation work at the French Limited site was performed from 1983 to 1985 by Lockwood, Andrews & Newnam, Inc. (LAN) under contract to the Texas Department of Water Resources and in cooperation with the EPA. From the *Remedial Investigation Report* of that effort (LAN, 1985) are drawn groundwater level data, water quality data and information pertaining to surface water flow directions. In late 1983, the French Limited Task Group was formed. Resource Engineering, Inc. (REI, subsequently ERT and now ENSR) was retained by the Task Group to provide technical consulting services From the *Remedial Investigation Report* prepared for the Task Group (REI, 1986a) are drawn bore hole data, cone penetrometer test data, groundwater level data, and limited geochemical data. This document was accepted by the EPA as the Final Remedial Investigation (RI) Report for the site after resolution of certain technical issues. These technical issues were addressed in a document titled *1986 Field Investigation Report* (REI, 1986b) containing bore hole, cone penetrometer, groundwater level, and geochemical data which are pertinent to this report Also issued in 1986 in response to the technical issues was a study of the confining properties of the middle clayey zone (see Section 2.2.2 below) titled *1986 Field Investigation Hydrology Report* prepared by Applied Hydrology Associates (AHA, 1986). From that report are drawn aquifer test data and interpretations and water level information.

In December of 1986 a large-scale field program was initiated to test the feasibility of biodegradation of the waste constituents in the French Limited Lagoon. The *In Situ Biodegradation Demonstration Report* (ERT, 1987) documents the voluminous information gathered during the program. From this report are taken bore hole data, groundwater level data, and geochemical data. In 1987, Lockwood, Andrews & Newnam, Inc. under contract to the U S. EPA released the *Endangerment Assessment for the French Limited Site* (LAN, 1987) In 1988 Jacobs Engineering Group, under contract to Region VI of the U.S. EPA, sampled the residential wells of the Riverdale Subdivision; data from their *Summary Report for Riverdale Subdivision Residential Well Monitoring* (JEG, 1988) are utilized here in the discussion of solute transport in the shallow groundwater system (Section 4.0 below).

In 1988 ENSR issued three reports from which numerous data have been drawn for this report. The first was the *Master Monitor Well Data Report, French Limited Site* (ENSR, 1988a) which is a compilation of all historic monitor well data. The second was *Site Survey Report* (ENSR, 1988b) which is a detailed survey of the French Limited site and environs including locations and elevations of monitoring wells. Table 1-1 presented here is a summary of the monitoring well data taken from ENSR (1988b). The third report was *Soil Vapor Survey* (ENSR, 1988c) from which are taken data pertaining to solute transport in the shallow groundwater system (Section 4.0 below).

1.3 REPORT ORGANIZATION

Section 2 of this report will address the regional geologic setting and the site-specific geology and physiography of the French Limited site. Section 3 of this report will focus upon the hydrogeology of the near-surface geologic units because there is documented evidence of groundwater contamination within these shallow units. Included in that section will be a discussion of water level (potentiometric) information; aquifer pumping test results; geologic controls on groundwater flow and hydrologic characteristics; and the influence of surface water, precipitation, evapotranspiration, and regional pumping on the shallow groundwater hydrology of the site area. Section 3 will conclude with calculations and a discussion of rates and directions of groundwater flow within the shallow geologic units. Section 4 of this report will discuss solute transport in the shallow groundwater of the site area. In that section the likely extent of contaminant migration that has occurred to date is identified The Summary and Conclusions are provided in Section 5 The definitions and the concepts of many technical terms used in this report are presented as an attachment at the end of the report.

The original data and the detailed discussion and interpretation of individual pumping tests conducted at the site are included as appendices to the main report in a separate volume. Results of the aquifer test of the upper alluvial zone conducted at well REI-3-3 during the 1986 field program are provided in Appendix A. Appendix B includes the results of the aquifer tests completed in 1988. Historic water depth information for the upper alluvial zone are included in Appendix C. Water level elevation data and hydrographs of select wells for the upper alluvial zone are included in Appendix D.

TABLE 1-1
MASTER MONITOR WELL DATA LIST
FRENCH LIMITED PROJECT

WELL NUMBER	ELEVATION TOP OF CASING FT, MSL	GRND SURFACE FT, MSL	CASING TYPE	CASING LENGTH FT	SCREEN ID	SLOT SIZE INCHES	LENGTH FT	DEPTH FT FROM	TO	NOTES ON WELL CONDITION
GW-2	18.35	16.4	PVC	38	4	?	20	38	58	
GW-3	NOT LOCATED FOR SURVEY		PVC	7	4	?	20	7	27	
GW-5	NOT LOCATED FOR SURVEY		PVC	5	4	?	20	5	25	
GW-7	18.36	16.4	PVC	14	4	?	10	14	24	
GW-8	12.91	13.5	CONSTRUCTION AND BORING LOG NOT FOUND							DESTROYED
GW-9	15.00	15.1	CONSTRUCTION AND BORING LOG NOT FOUND							
GW-12	13.21	11.0	PVC	132	4	?	20	132	152	
GW-13	12.95	10.9	PVC	4	2	?	20	4	24	
GW-15	NOT LOCATED FOR SURVEY		PVC	3	2	?	20	3	23	
GW-16	NOT LOCATED FOR SURVEY		PVC	3.5	2	?	20	3.5	23.5	
GW-17	17.03	15.3	PVC	3	2	?	20	3	23	
GW-18	16.25	15.3	PVC	3.5	2	?	20	3.5	23.5	
GW-19	16.04	13.7	PVC	3.5	2	?	20	3.5	23.5	
GW-20	NOT LOCATED FOR SURVEY		PVC	3	2	?	20	3	23	
GW-21	NOT LOCATED FOR SURVEY		PVC	1.3	2	?	20	1.3	21.3	
GW-22	NOT LOCATED FOR SURVEY		PVC	3.5	2	?	20	3.5	23.5	
GW-23	11.65	9.9	PVC	13	2	?	5	13	18	
GW-24	NOT LOCATED FOR SURVEY		PVC	18	2	?	5	18	23	
GW-25	NOT LOCATED FOR SURVEY		PVC	145	2	?	5	145	150	REMOVED
MR-2	13.27	10.2	CONSTRUCTION AND BORING LOG NOT FOUND							
MR-3	11.65	9.2	CONSTRUCTION AND BORING LOG NOT FOUND							
MR-4	12.35	9.3	CONSTRUCTION AND BORING LOG NOT FOUND							
P101	18.75	16.6	CONSTRUCTION AND BORING LOG NOT FOUND							
REI-1	23.48	21.5	PVC	3	2	0.010	5	3	8	
REI-3-1	12.68	10.2	PVC	41	4	0.010	10	41	51	DESTROYED
REI-3-2	12.46	10.3	PVC	28	4	0.010	5	28	33	
REI-3-3	13.11	10.3	PVC	8.5	4	0.010	14	8.5	22.5	
REI-3-4	14.03	10.4	PVC	120	4	0.010	25	120	145	
REI-3-5	NOT LOCATED FOR SURVEY		PVC	6.5	4	0.010	15.8	6.5	22.3	
REI-4-1	NOT LOCATED FOR SURVEY		PVC	36	4	0.010	15	36	51	
REI-4-2	NOT LOCATED FOR SURVEY		PVC	6.5	4	0.010	15	6.5	21.5	
REI-5	22.39	19.1	PVC	6.9	2	0.010	10	6.9	16.9	
REI-6-1	13.94	12.2	PVC	30	4	0.010	20	30	50	
REI-6-2	14.58	13.2	PVC	5	4	0.010	20	5	25	
REI-7	13.38	11.5	PVC	121	4	0.010	15	121	136	
REI-8	15.52	12.5	PVC	13	2	0.010	10	13	23	
REI-9	18.79	15.5	PVC	12	2	0.010	10	12	22	
REI-10-1	12.90	13.0	PVC	122.7	4	0.010	25.3	122.7	148	
REI-10-2	14.24	12.9	PVC	34.2	4	0.010	13.8	34.2	48	
REI-10-3	13.91	14.2	PVC	37.7	4	0.010	10.3	37.7	48	
REI-10-4	14.18	14.2	PVC	35.2	4	0.010	12.8	35.2	48	
REI-11	11.78	9.9	PVC	135.9	4	0.010	16.6	135.9	152.5	
REI-12-1	12.53	10.4	PVC	114.5	4	0.010	36.5	114.5	151	
REI-12-2	12.25	10.3	PVC	35.3	4	0.010	15.2	35.3	50.5	

Source: ENSR (1988a)

TABLE 1-1
MASTER MONITOR WELL DATA LIST
FRENCH LIMITED PROJECT

WELL NUMBER	ELEVATION TOP OF CASING FT, MSL	GRND SURFACE FT, MSL	CASING TYPE	LENGTH FT	SCREEN ID	SLOT SIZE INCHES	LENGTH FT	DEPTH FT FROM	TO	NOTES ON WELL CONDITION
REI-P10-2	14.29	14.0	PVC	90	4	0.010	2	90	92	
REI-P10-3	13.95	13.7	PVC	82	2	0.010	2	82	84	
REI-P10-4	15.23	13.7	PVC	80	2	0.010	2	80	82	
ERT-1	15.18	15.2	PVC	20	4	0.010	30	20	50	
ERT-1A	14.57	14.9	PVC	5	4	0.010	15	5	20	
ERT-2	15.52	15.9	PVC	17.5	4	0.010	32.5	17.5	50	
ERT-3	16.33	16.6	PVC	20	4	0.010	28	20	48	
ERT-4	15.03	15.3	PVC	19.5	4	0.010	27.5	19.5	47	
ERT-4A	14.51	14.9	PVC	5.5	4	0.010	15	5.5	20.5	*
ERT-5	15.81	16.1	PVC	20	4	0.010	30	20	50	
ERT-6	15.70	16.0	PVC	20	4	0.010	30	20	50	
ERT-7	13.33	13.9	PVC	17.7	4	0.010	28	17.7	45.7	
ERT-7A	13.86	14.2	PVC	5	4	0.010	15	5	20	
ERT-8	13.41	14.1	PVC	19.6	4	0.010	29.5	19.6	49.1	
ERT-8A	14.00	14.1	PVC	5	4	0.010	15	5	20	
ERT-9	14.39	14.8	PVC	22	4	0.010	30	22	52	
ERT-9A	14.25	14.7	PVC	5	4	0.010	15	5	20	
ERT-10	14.58	14.8	PVC	20	4	0.010	30	20	50	
ERT-10A	14.20	14.7	PVC	5	4	0.010	15	5	20	
ERT-20	13.79	11.2	PVC	7	4	0.010	35	7	42	
ERT-21	13.09	10.4	PVC	7	4	0.010	35	7	42	
ERT-22	11.24	9.6	PVC	8	4	0.010	40	8	48	
ERT-23	15.87	12.5	PVC	15	4	0.010	40	15	55	
ERT-24	13.01	10.0	PVC	10	4	0.010	35	10	45	
ERT-25	15.42	13.0	PVC	8	4	0.010	40	8	48	
ERT-26	13.27	11.2	PVC	8	4	0.010	40	8	48	
ERT-27	16.13	14.3	PVC	8	4	0.010	40	8	48	
ERT-28	19.82	17.8	PVC	8	4	0.010	55	8	63	
ERT-29	19.37	17.7	PVC	8	4	0.010	50	8	58	
ERT-30	17.35	15.8	PVC	8	4	0.010	45	8	53	

* DATA TAKEN FROM FIELD LOG BOOK; BORING AND CONSTRUCTION LOGS NOT FOUND
ALL ELEVATIONS AS OF 8-31-88

Source: ENSR (1988a)

2.0 GEOLOGIC SETTING

The French Limited site is located within the alluvial plain of the San Jacinto River approximately six miles north of the river's confluence with the Houston Ship Canal (Figure 2-1). The site is subject to flooding of the San Jacinto River due to its low-lying nature. The near-surface geology of the site is dominated by the alluvial deposits of the San Jacinto River and the underlying strata of the Beaumont Formation

2.1 REGIONAL GEOLOGY

The French Limited site is in the Coastal Plain Region, which consists of sedimentary materials deposited by formerly and presently active geologic processes in deltaic, alluvial, eolian dune, bay-estuarine, and barrier-island-shoreline systems. The Southeast Texas portion of the Coastal Plain is underlain by a thick mass of sediments (in excess of 30,000 feet) that are now dipping slightly toward the Gulf of Mexico. Upper sections of the coastal plain have been considerably eroded. Successively older geologic formations outcrop progressively farther inland from the coast line (Figure 2-2) (LAN, 1985).

The deposits of the Southeast Texas Coastal Plain are mainly of the Tertiary Period (70 million to three million years old), and Quaternary Period (three million years old to present). The Quaternary Period is subdivided into the Pleistocene (three million to 0 2 million years old) and the Holocene (0.2 million years old to present) epochs Holocene deposits in the area of the French Limited site consist of river alluvium. Remnants of early Holocene alluvial deposits (Deweyville Formation) exist at the surface (Figure 2-3) and beneath the site area based on mapping performed by the Texas Bureau of Economic Geology in 1968. Most of the surficial deposits in the site area are later Holocene (Recent) alluvium.

The Holocene deposits are underlain by the differentiated formations (Beaumont, Montgomery, Bentley and Willis) of the Pleistocene epoch, which form a very smooth, gently seaward-tilted plain. The differentiated formations comprise the Chicot aquifer identified in Figure 2-2. The near-surface formation is the Beaumont consisting of clays with interbedded silts and sands which have been deposited by river deltas and floodplains. Subsequent to their deposition, the Beaumont sediments were desiccated when the sea levels were much lower than they are presently. Consequently, the Beaumont sediments are overconsolidated, generally have high strengths and typically have a blocky secondary structure with some slickensides (LAN, 1985).

The low relief characteristic of the Coastal Plain is occasionally disrupted by entrenched streams. These include channels that cut across the plain and are actively growing through the process of headward erosion (LAN, 1985).

Withdrawal of groundwater from deep formations has caused ground faulting in the Houston area. Based upon a review of available data sources, no known faults pass through or near the site area. Another phenomenon related to

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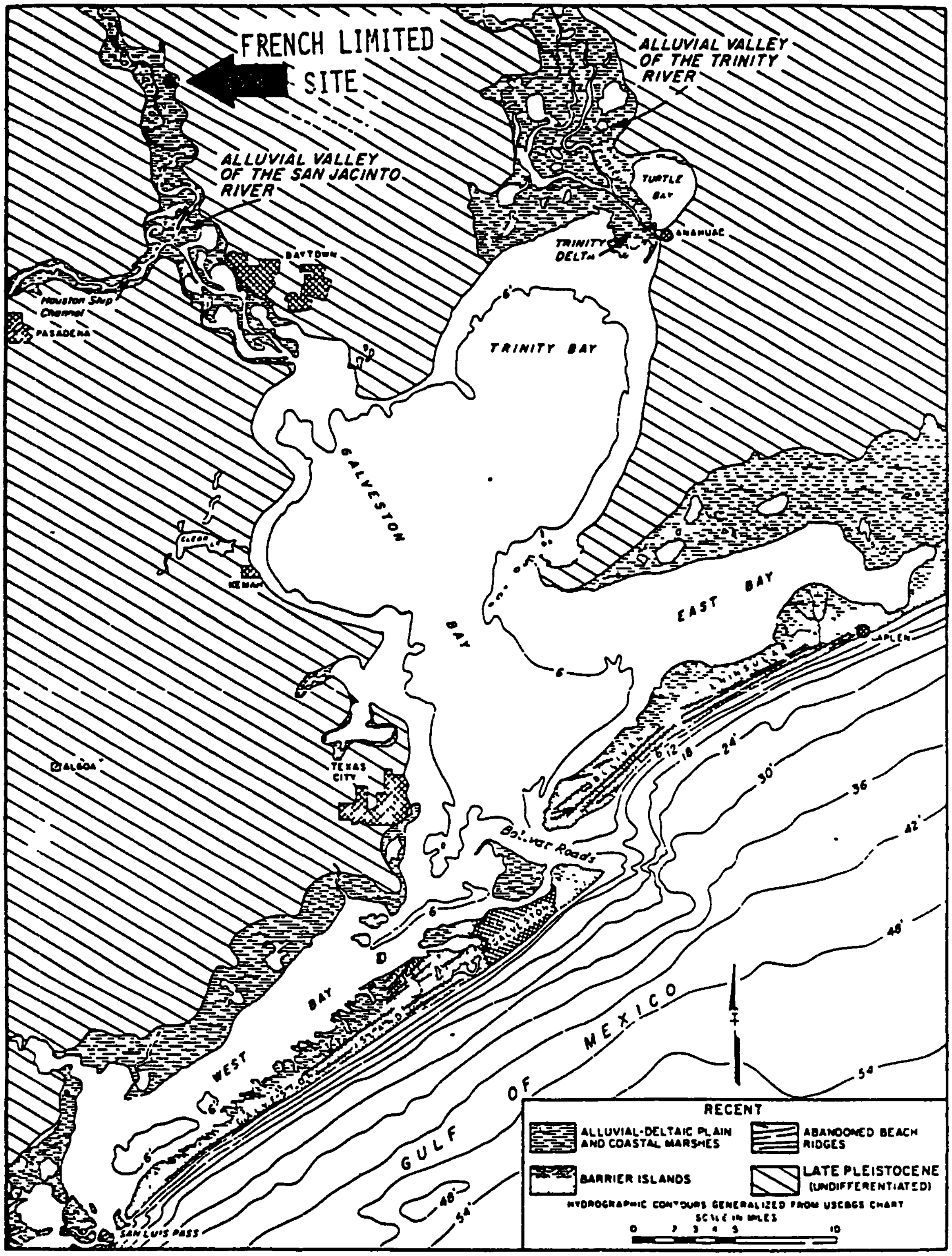
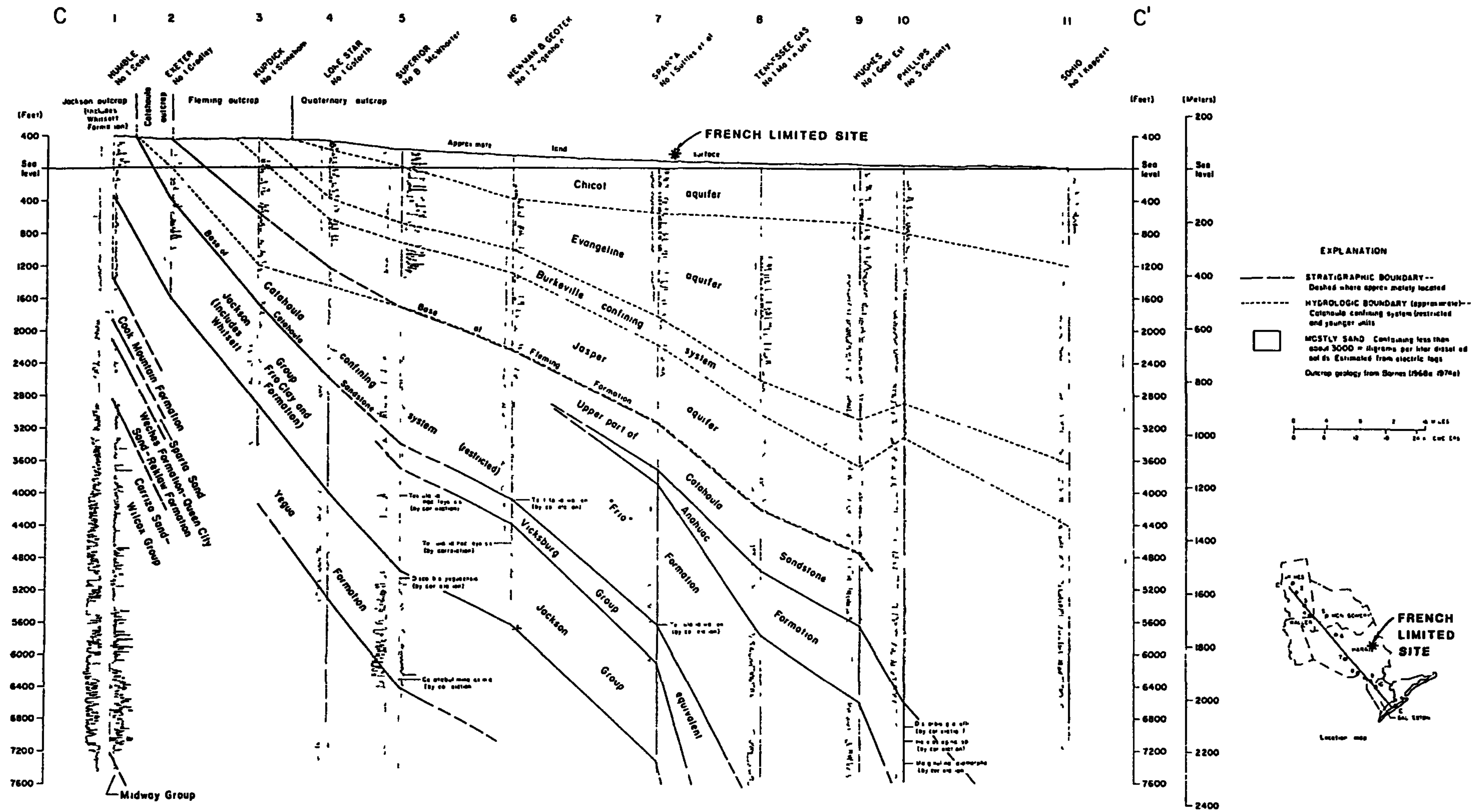


Reference : TRANSACTIONS, Gulf Coast Geographical Society. Vol. 9 1959, p. 209

Adapted from Figure 2-3. Resource Engineering Inc. 1986a, Remedial Investigation Report, French Limited Site.

FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 2-1
LOCATION MAP
FRENCH LIMITED SITE

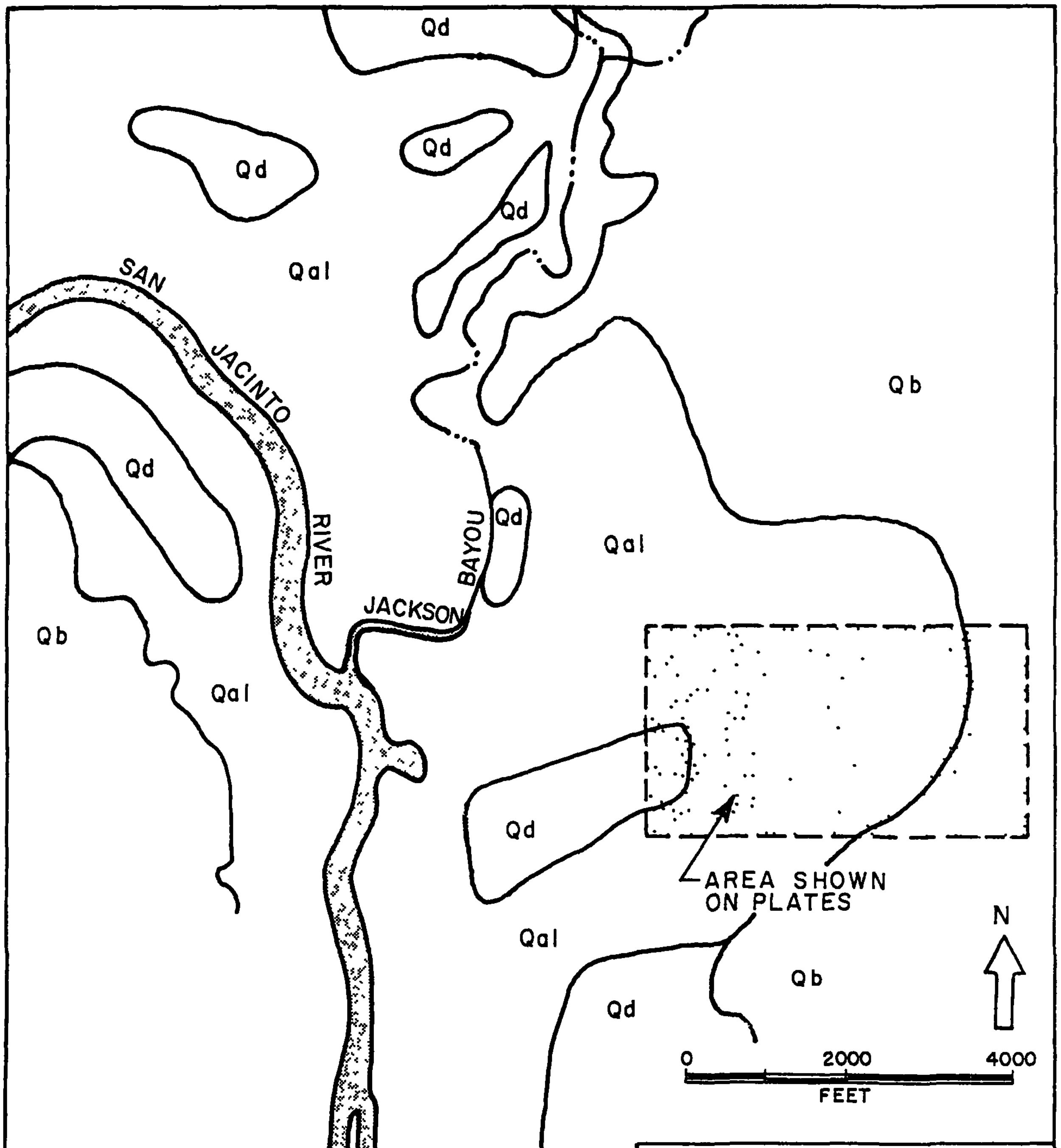


SOURCE <u>STRATIGRAPHIC AND HYDROGEOLOGIC FRAMEWORK OF PART OF THE COASTAL PLAINS OF TEXAS,</u>
TEXAS DEPARTMENT OF WATER RESOURCES REPORT #236, JULY, 1979

Stratigraphic and Hydrogeologic Section C-C
From TDWR Report #236

FIGURE 2-2

C9437



LEGEND

Qal – RECENT ALLUVIUM, CLAY, SILT AND SAND DEPOSITED BY THE SAN JACINTO RIVER

Qd – DEWEYVILLE FORMATION. RECENT OR LATE PLEISTOCENE ALLUVIUM, SAND, SILT AND CLAY

Qb – BEAUMONT FORMATION. PLEISTOCENE ALLUVIUM, CLAY, SILT AND SAND

REFERENCE: BUREAU OF ECONOMIC GEOLOGY, 1968

FRENCH LIMITED TASKGROUP, INC
FRENCH LIMITED SITE
CROSBY, TEXAS

FIGURE 2-3
SURFICIAL GEOLOGY OF SITE

PROJECT NUMBER 26

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withdrawals of groundwater in the Houston area is subsidence which has exceeded eight feet over the past 75 years. Based on elevation corrections of USGS Bench Mark D690, approximately 4,000 feet to the west, the French Limited site subsided 0.93 feet between 1963 and 1973 and 0.32 feet between 1973 and 1978 (LAN, 1985). All elevations used in this report have been adjusted to the most recent survey of the site (ENSR, 1988) for consistency.

2.2 SITE GEOLOGY

Plate 1 shows the French Limited site and the location of bore holes, monitoring wells, and cone penetrometer tests that have been used to characterize the stratigraphy of the site. Cross Sections A-A', B-B', C-C', and D-D' and the Fence Diagram of the site, all located in map pockets which precede the appendices of this report, depict the geology of the French Limited site.

Cross Sections A-A' and B-B' and the Fence Diagram have been constructed exclusively from cone penetrometer test data presented by REI for the *Remedial Investigation Report* (1986a) and the *1986 Field Investigation Report* (1986b); cone penetrometer tests performed for each report are respectively labeled C-#-85 and CPT-# on Plate 1 where # is the site number. These data were preferred over many of the lithologic data presented in ENSR (1988a) because of the continuous, non-subjective records of sleeve friction, tip resistance, and the ratio of sleeve friction to tip resistance (percent ratio). The total data for these three parameters are presented in Supporting Data for Cross Section A-A', Supporting Data for Cross Section B-B' (which encompasses two sheets), and Supporting Data for Fence Diagram (encompassing two sheets) which are also located in the map pockets For clarity, only the data plots of the percent ratio of sleeve friction to tip resistance are presented in Cross Sections A-A', B-B', and the Fence Diagram.

Cross Sections C-C' and D-D' have been constructed from a combination of cone penetrometer test data and bore hole data where the bore holes were geophysically logged. On Cross Sections C-C' and D-D' the lithologic descriptions of the bore holes are accompanied by gamma ray and resistivity geophysical logs. Geophysical logs are of great assistance in interpreting a geologist's description of the lithology of a bore hole by virtue of the logs providing accurate depths to lithologic contacts and a measure of the lithologic type and variability of a geologic stratum. There are no geophysical logs for bore holes GW-1 (Cross Section D-D') or GW-12 (Cross Section C-C'); however, the lithologic descriptions for these bore holes were included to extend the range of the respective cross sections.

The use of non-subjective cone penetrometer test and geophysical data in constructing the cross sections and Fence Diagram has resulted in a good representation of the site geology. This representation is be free of the inherent inconsistencies of many individuals describing bore hole lithologies over a period of several years. However, interpretation by qualified geologists has been necessary to relate the cone penetrometer test and geophysical information from one location to another

Based on the data presented, it has been determined that the upper stratigraphy of the French Limited site and environs can be divided into three zones: an upper alluvial zone, a middle clayey zone, and a lower silty-sand zone. Descriptions of these zones, from lower to upper, follow.

2.2.1 Lower Silty Sand Zone

The lower silty sand zone is comprised of a poorly consolidated water-bearing silty sand, sandy silt, and silty clay. The top of this zone occurs at a depth of approximately 109 to 137 feet below ground surface (elevation of -97 to -125 feet). The top of this zone is defined by a silty sand stratum which is apparently continuous below the French Limited site and environs (see Cross Sections C-C' and D-D') and ranges from six to 14 feet in thickness. Sands, silty sands, and silty clays underlie this stratum to an undetermined depth. This lower zone may represent a sandy zone within the Beaumont Formation or the upper part of the Montgomery Formation which underlies the Beaumont.

2.2.2 Middle Clayey Zone

The middle clayey zone consists of 61 to 93 feet of thinly interbedded silty clays, clayey silts, and silty sandy clays of the Beaumont Formation. This zone becomes more sandy with depth. The top of the middle clayey zone occurs at about 43 to 55 feet below ground surface (elevation of -32 to -45 feet). At the top of this zone is a discontinuous silty clay, sandy silty clay, and clay stratum identified as C2 on the cross sections and Fence Diagram. This stratum is up to 24 feet in thickness. Underlying the C2 stratum is a clayey silt and silty clay stratum indicated as C3 on the cross sections and Fence Diagram. This stratum is continuous below the French Limited site and environs and is seven to 15 feet thick. The clays of the middle clayey zone are characteristically reddish-brown or blue-grey with reddish mottling, are blocky in texture and contain slickensides. The middle clayey zone is an aquitard which isolates the groundwater of the upper alluvial zone from the lower silty sand zone (see Section 3 3 2 below).

2.2.3 Upper Alluvial Zone

The upper alluvial zone consists of poorly consolidated sands, silty sands, gravels, and clay strata deposited in an meander belt of the San Jacinto River that is now abandoned. The processes leading to the formation of alluvial deposits give rise to a variety of sediments. As a river meander gradually advances across a valley, it erodes older deposits on the outside of the bend and deposits predominantly sandy material on the inside of the bend (point bar deposits). Eventually, the meander doubles back on itself and the river takes a direct path, cutting off the meander which then becomes an oxbow lake. During flooding, the lake fills with silts and clays. As the river continues to meander back and forth across the valley over geologic time, the older deposits are periodically eroded and new alluvium is deposited adjacent to the old. This process has resulted in the alluvial deposits encountered at the French Limited site. Because of the nature of their deposition, the grain size of the deposits varies laterally and vertically across the site (LAN, 1985).

The upper alluvial zone is mostly saturated and due to its sandy nature yields water to wells. The upper alluvial zone is up to approximately 55 feet thick and thins out to zero thickness at the margins of the abandoned meander belt to the south and east of the French Limited lagoon (see Cross Section D-D').

The geologic information from a number of bore holes and cone penetrometer tests indicates a high degree of vertical and lateral grain-size variation within the upper alluvial zone which is typical of alluvial deposits. However, the geologic interpretation suggests that the unit may be subdivided into four distinct heterogeneous strata which have appreciable lateral extent. The uppermost uncompacted stratum (unit UNC on the cross sections and Fence Diagram) is up to 18 feet thick and is comprised mostly of loose silty sands which pose little resistance or friction to a cone penetrometer. This unit represents the most recent deposits of the San Jacinto River. In the vicinity of roads this stratum includes fill material while at the abandoned Harris County landfill, this stratum is comprised of debris. The uncompacted stratum may be present across the entire French Limited site and vicinity although it is not indicated on the log of bore hole REI-12-1 (Cross Section D-D'). The geophysical data for bore hole REI-12-1 do not conclusively indicate either the presence or absence of the uncompacted stratum at that site. The uncompacted stratum has been removed by dredging at the French Limited Lagoon and South Pond.

Underlying the uncompacted stratum is a sandy stratum (unit S1 on the cross sections and Fence Diagram) that is four to 26 feet thick and appears to be continuous below the French Limited site and environs except at cone penetrometer test site CPT-11, the French Limited Lagoon, and South Pond Some gravels occur in the S1 stratum Apparently the dredging operations which created the French Limited Lagoon and the South Pond were exploiting the sands of the uncompacted and S1 strata, for both bodies of water end at the base of the S1 stratum.

Underlying the sandy S1 stratum is a silty clay, silty sandy clay, and clay stratum indicated as C1 on the cross sections and Fence Diagram. This stratum is two to 17 feet thick and appears to be continuous below the entire French Limited site and vicinity except at cone penetrometer test site C-5-85. Underlying the C1 stratum is a stratum comprised of nine to 24 feet of interbedded silts, clays, and sands indicated as INT on the cross sections and Fence Diagram. This stratum also appears to be continuous below the entire French Limited site and environs and forms the base of the upper alluvial zone.

3.0 HYDROGEOLOGIC SETTING

The hydrogeology of the French Limited site is controlled to a large extent by the close proximity of the San Jacinto River. The site is low lying and subject to frequent flooding. There are numerous ponds and swamps in the vicinity of the site. Groundwater occurs in the shallow aquifer of the upper alluvial zone of an abandoned meander belt of the river.

3.1 PHYSIOGRAPHY

Measured surface elevations at the French Limited site range from 10 to 16 feet above mean sea level (MSL). The topography of the site is associated with the alluvial valley of the San Jacinto River. To the west of the site, the ground surface rises about six feet in a microfeature of the floodplain upon which is built the Riverdale Subdivision. This microfeature correlates with an outcrop of early Holocene alluvium (Deweyville Formation) mapped by the Bureau of Economic Geology in 1968 (Figure 2-3). To the east of the site, ground surface rises rapidly about 20 feet along a former levee that marks the former eastern extent of the meander belt of the San Jacinto River. This corelates with the outcrop of Beaumont Formation in this area as shown in Figure 2-3. A detailed survey of the French Limited site and environs is presented in ENSR (1988b).

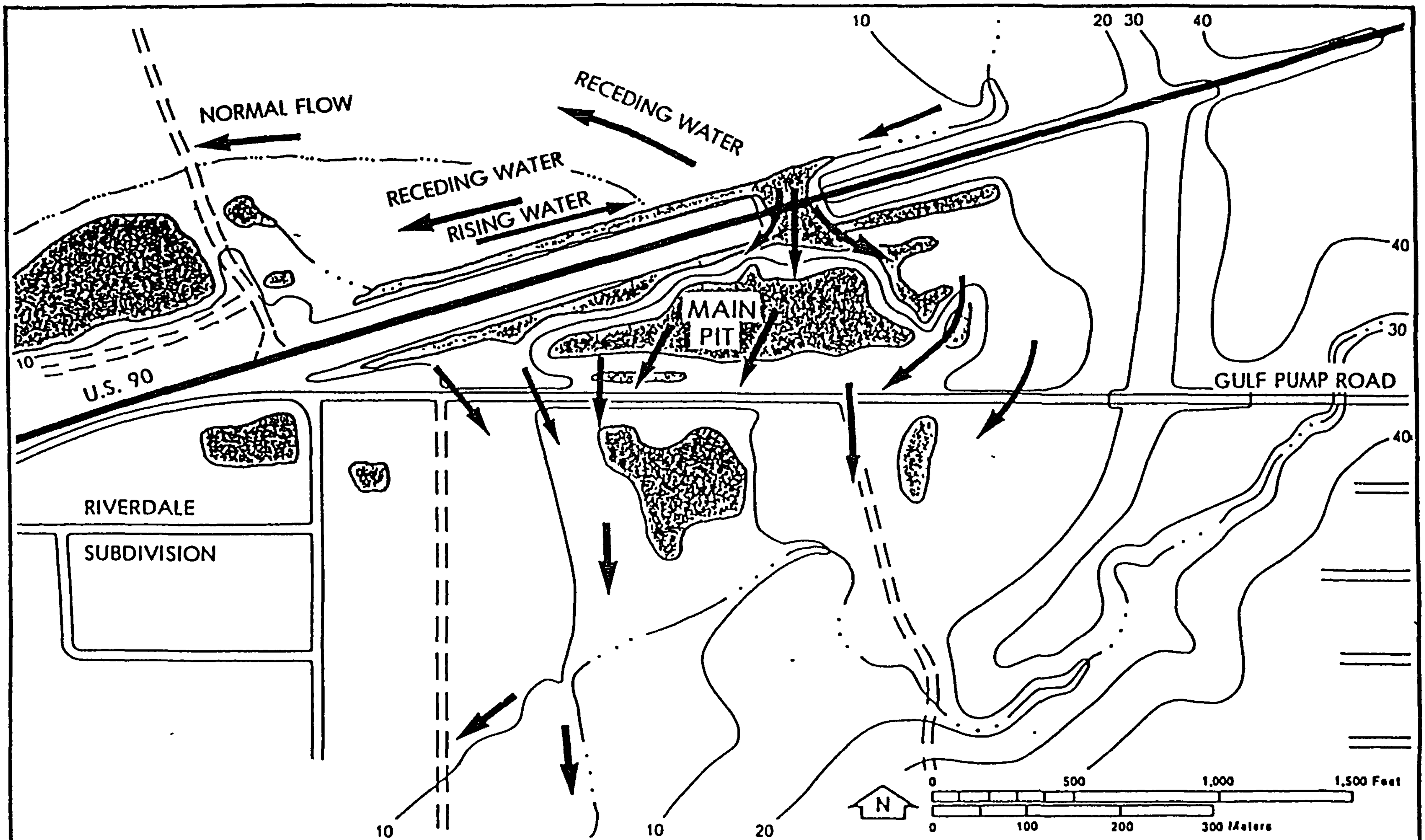
The general surface water flow pattern of the site is southwest toward the San Jacinto River. The drainage of the site and adjacent areas is poor and generally dominated by man-made features such as roads, ditches, culverts, berms, pits, and garbage dumps or fill areas. Following repeated flooding, the French Limited Lagoon and a small pit to the east were bermed with no regularly flowing outlet (LAN, 1985)

The fishing hole in the swampy area beneath the U S Highway 90 bridge and to the north of the French Limited Lagoon drains northward and then to the west along the north side of U.S. Highway 90 (Plate 1). Flow passes through a series of marshes and culverts, just north of U.S Highway 90, eventually reaching the San Jacinto River some 6,000 feet to the west. The marsh area east of the French Limited Lagoon is also in this drainage area (LAN, 1985).

The abandoned sand pit south of the site is referenced in this report as the South Pond. This pond drains into an unnamed stream (Plate 1) which enters Rickett Lake some 4,800 feet to the southwest. The unnamed stream is the main natural drainageway for the French Limited site and appears to influence the near-surface groundwater flow pattern (LAN, 1985).

According to the Harris County Building Permits Division and the U.S. Army Corps of Engineers, the 100-year floodplain elevation in the vicinity of the site is 28 feet above MSL. Thus the entire site and Riverdale Subdivision is within the 100-year floodplain. Discharges less than the 100-year flood have covered the site in 1969, 1973, 1979, and 1983 (LAN, 1985). Figure 3-1 illustrates the direction of flood flows at the site.

Several pits resulting from mining of shallow sand deposits exist in the vicinity of the French Limited site. These pits strongly influence the



Adopted from Figure 5-1, in Lockwood, Andrews & Neuman, 1985.
Remedial Investigation Report, French Limited Site

FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 3-1

FLOOD FLOW PATTERNS
MAY 23-24, 1983

local hydrogeology. The French Limited Lagoon was formed via hydraulic dredging conducted by a sand mining operation from the late 1950's until about 1965. Bottom profiling of the lagoon was performed by both LAN (1985)and REI (1986a) the results of which are depicted in Figure 3-2. The lagoon has steep banks except at the west end and has a maximum depth of about 19 feet. However, because of sludge accumulation in the lagoon, the actual depth of the lagoon when it was abandoned around 1965 was about six to 10 feet deeper (approximately 25 to 30 feet deep). The surface elevation of the French Limited Lagoon was surveyed at 9.5 feet during the summer of 1988 (ENSR, 1988b)

Data presented by LAN (1985) indicate that the South Pond is about three acres in size and 15 to 17 feet deep with up to two feet of black gelatinous liquid lying on the bottom. Low concentrations of benzene (0.045 ppm), phthalates (21-23 ppm), naphthalene (0 12 ppm), flouranthrene (0 059 ppm) and pyrene (0.078 ppm) were identified in a sediment sample (LAN, 1985). Further investigation of the South Pond sediments and water is planned (see section 5.3 for recommendations) The surface elevation of this pond was surveyed at 9.0 feet during the summer of 1988 (ENSR, 1988b).

Other abandoned sand pits that are now ponds occur in the vicinity of the site. The bathymetry of these ponds and the various swampy areas about the site has not been investigated. The ponds are likely 15 to 20 feet deep as judged by their areal extent and the depth of the French Limited Lagoon and the South Pond while the swampy areas are likely a maximum of about 10 feet deep ENSR (1988b) identifies the surface elevations of these various ponds and swampy areas.

Southwest of the French Limited Lagoon is the Harris County landfill which was used in the late 1960's for the disposal of construction and demolition debris and other miscellaneous wastes. The approximate location of the now closed landfill is depicted on Plate 1. The drill logs of monitor wells REI-1, REI-5, and ERT-23 presented in ENSR (1988a) indicate the presence of trash, broken glass, concrete, and oily brown-to-black soil with a strong odor to a depth of eight to 14 feet.

3.2 CLIMATIC SETTING

The climate of the French Limited site can be broadly characterized as subtropical spring through fall with occasional polar outbreaks during the fall and spring. During the winter, the area is subject to frontal passages of polar air with short, but not uncommon, periods of subfreezing weather (REI, 1986a). The annual average temperature is 69 degrees Fahrenheit, with monthly averages at a minimum in January (52°F), and at a maximum in July and August (83°F) (REI, 1986a).

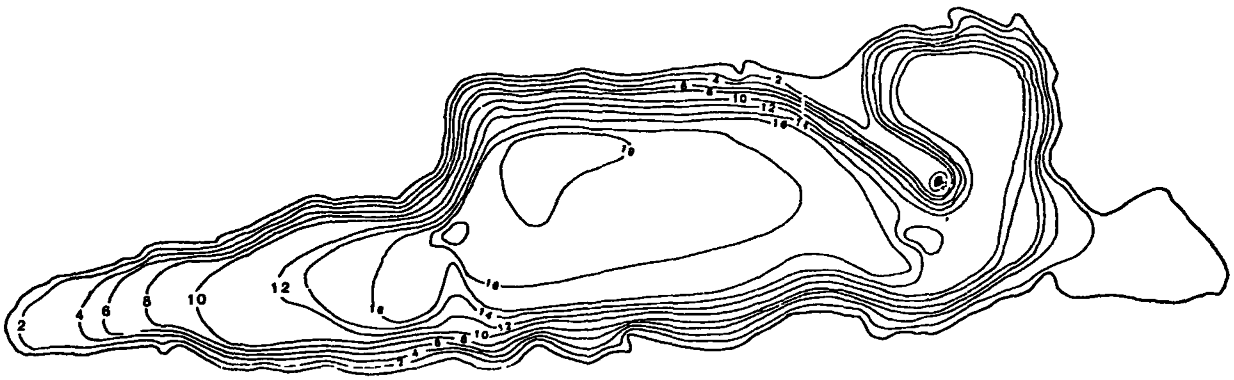
The French Limited site experiences approximately 52 inches of rain per year with the greatest seasonal rainfall occurring during the late spring to early summer and early fall months. Precipitation at the San Jacinto Dam just north of the site has ranged from 35.03 to 180.27 inches per year with an average of 52.16 inches per year over the last 20 years. Gross surface evaporation rates for the same period have ranged from 43.2 to 55.8 inches per year with an average of 49.91 inches per year. Evaporation rates are typically greatest in the summer months with the months of December,

LAN BOTTOM PROFILING
SURFACE DATUM APPROXIMATELY X +10 6' MSL

REFERENCE REMEDIAL INVESTIGATION REPORT
LOCKWOOD ANDREWS & NEWMAN INC APRIL 1985

N

0 100 200
SCALE IN FEET



REI BOTTOM PROFILING
SURFACE DATUM APPROXIMATELY +10 5' MSL

FRENCH LIMITED PROJECT CROSBY, TEXAS		
FIGURE 3-2 FRENCH LIMITED LAGOON BOTTOM CONTOURS (ADAPTED FROM FIGURE 3-5 IN RESOURE ENGINEERING, INC 1986 REMEDIAL INVESTIGATION REPORT, FRENCH LIMITED SITE)		
PROJECT No 26	DATE 1-10-89	REVISION

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER CO

January, and February experiencing the lowest rates (LAN, 1985). Evapotranspiration (the total of pond evaporation, evaporation of soilwater, and plant transpiration losses) at the site has not been quantified but likely approximates the mean annual precipitation of 52 inches.

3.3 HYDROGEOLOGY OF THE SITE

The primary objective of the hydrogeologic characterization and related field investigations is to determine the properties of the various geologic units that control the pathways and rates of possible contaminant migration in the groundwater system in the vicinity of the French Limited Lagoon. This requires information on the nature and continuity of geologic units, the permeability, porosity, and elastic storage characteristics of these units and the energy state of water (i.e., potentiometric heads) that represent the driving force for groundwater and miscible contaminant movement.

The geologic units of major concern at the French Limited site are the upper alluvial zone and the middle clayey zone. As described in Section 2.2 3 of this report, the upper alluvial zone in the vicinity of the French Limited site is up to approximately 55 feet thick and overlies the middle clayey zone, a unit of silty clays and clayey silts of the Beaumont Formation. The upper alluvial zone is the unit containing the French Limited Lagoon. The overall influence of the middle clayey zone has been to confine the effects of contamination from the French Limited Lagoon to the upper alluvial zone. The middle clayey zone overlies the lower silty sand zone, a unit of poorly consolidated silty sands, sandy silts and silty clays that appears to be continuous in the immediate vicinity of the French Limited site The lower silty sand zone is of interest because it is the first aquifer below the aquiclude formed by the middle clayey zone.

A detailed evaluation of the hydrogeologic characteristics of these three hydrologic units is provided below

3.3.1 Lower Silty Sand Zone

The lower silty sand zone yields water easily to wells and is considered to be an aquifer using the classification criteria of Freeze and Cherry (1979) This zone is a confined saturated unit which appears to be continuous across the French Limited site and environs (see Section 2.2.1). It is the first significant sandy unit underlying the middle clayey zone. The lower silty sand zone is thought to be part of the Montgomery Formation which is part of the regional Chicot aquifer system (see Figure 2-2); however, it may represent a sandy zone within the Beaumont Formation.

3.3.1.1 Water Level Interpretation

Water levels in the lower silty sand zone are observed to respond to pumping within the zone and to blanket loads imposed by significant precipitation. This is illustrated by the water level response of well REI-11 during a 7-day pumping test of the lower silty sand zone during 1986 (Figure 3-3). Water levels in this well did not respond to changes in barometric pressure.

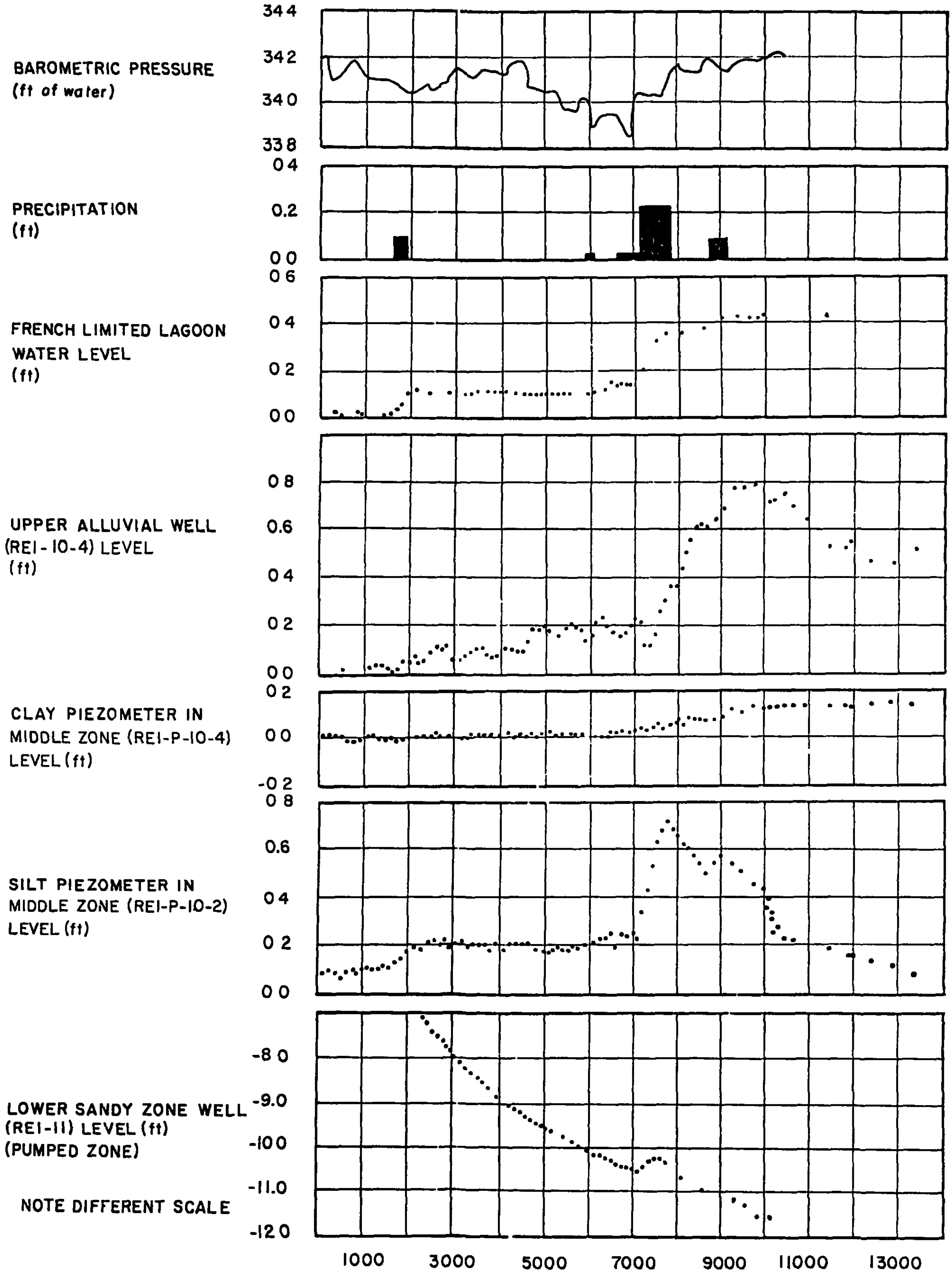


FIGURE 3-3 RESPONSE OF SELECT WELLS TO PRECIPITATION AND PUMPING IN THE LOWER SANDY ZONE

Lack of barometric response and the extremely efficient response to blanket precipitation loads, indicates the presence of an extensive confining unit of very low permeability that prevents vertical drainage of pore water (AHA, 1986). The lack of response also demonstrates the absence of permeable sand channels connecting the zone with the upper alluvial zone.

Potentiometric variation within the lower silty sand zone (as evidenced by water level elevations measured in 1986 in seven observation wells) indicates a general eastward hydraulic gradient of about 6.3 feet per mile which is 0.001 foot per foot (ft/ft) when rounded off (Plate 2). This gradient is apparently in response to municipal pumping by the town of Barrett since the regional gradient of the Chicot aquifer system is southerly towards the Gulf of Mexico.

3.3.1.2 Hydraulic Characteristics

The lower silty sand zone is characterized as a confined aquifer unit having variable geologic and hydrogeologic properties in the area investigated. The hydrogeologic characteristics of the lower silty sand zone were analyzed by several long term pump tests conducted during the 1986 field investigations. These tests are described in AHA (1986). The measured average hydraulic conductivity of the zone ranges from a high value of about 4×10^{-3} centimeters per second (cm/sec) based on tests conducted on the REI 10-1 well, to a low of 1×10^{-3} cm/sec based on testing of the REI 3-4 well Well yield in the REI 12-1 well indicates an average hydraulic conductivity within this range. The poor response of the REI-7 well to pumping of both the REI 3-4 and REI 10-1 wells indicates lower average hydraulic conductivities in the eastern section of the area investigated.

Using a mean hydraulic conductivity of 2 5×10^{-3} cm/sec (7.09 feet per day), a gradient of 0 001 ft/ft, and an assumed effective porosity of 0.1 results in a mean groundwater velocity of 0 07 feet per day (26 feet per year) easterly towards Barrett in the lower silty sand zone.

3.3.2 Middle Clayey Zone

The zone is saturated but due to its clayey nature does not yield water easily to wells and tends to restrict the transmission of groundwater to adjacent aquifers. A geologic unit having these types of characteristics is generally termed an aquitard or an aquiclude depending on the degree of transmission (Freeze and Cherry, 1979).

3.3.2.1 Water Level Interpretation

Water level data from the middle clayey zone have been collected from three piezometers, REI-P10-2, REI-P10-3 and REI-P10-4. Water level data from these piezometers are provided in Figure 3-4 along with the corresponding water levels in the upper alluvial zone and the lower silty sand zone at the same location. These data indicate a dramatic drop in potentiometric heads through the middle clayey zone. This drop in heads is equivalent to an average vertical hydraulic gradient of about 1.0 ft/ft.

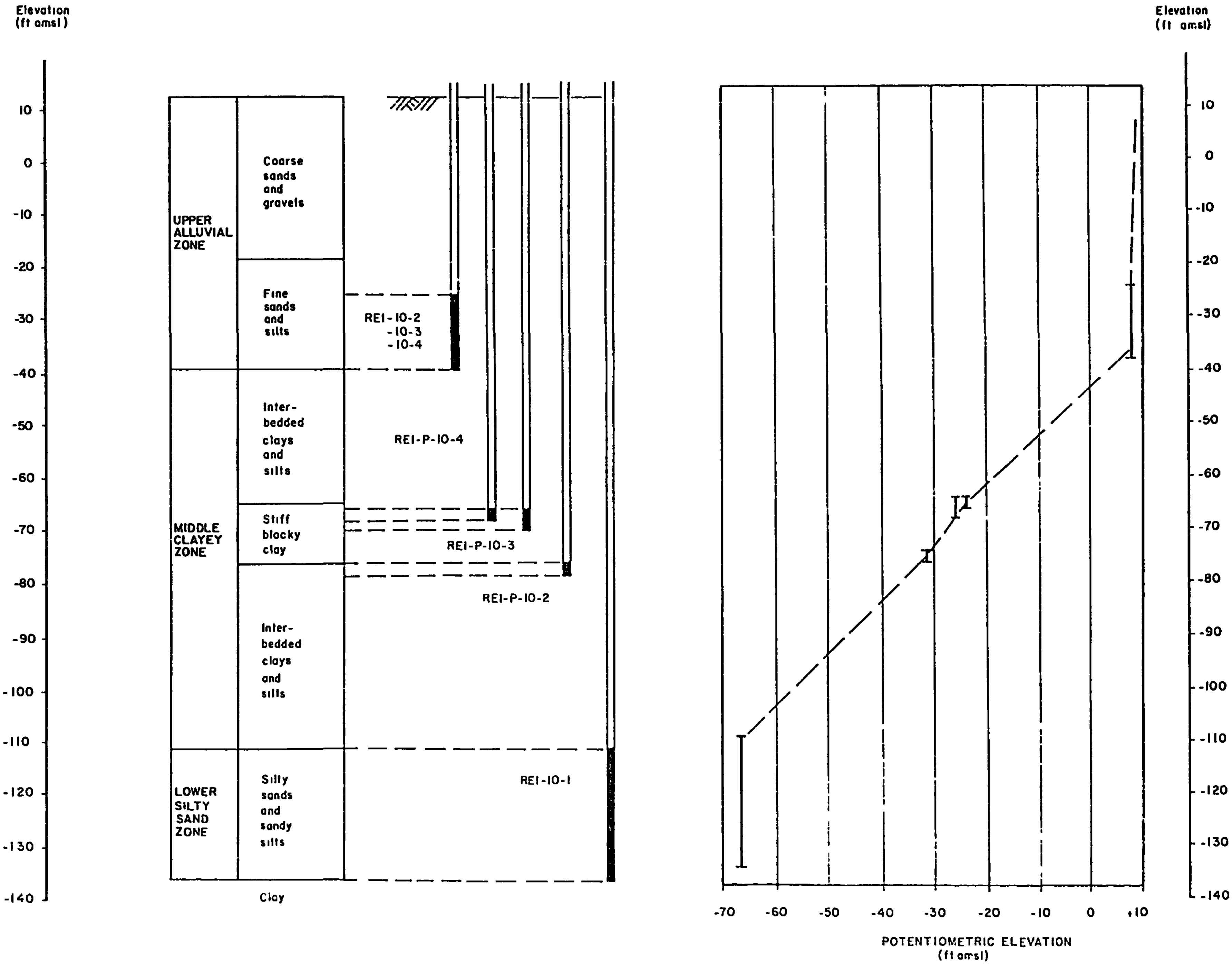


FIGURE 3-4 POTENTIOMETRIC VARIATION WITH DEPTH THROUGH THE MIDDLE CLAY ZONE

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Extensive regional pumping since the start of this century has resulted in considerable drawdown of potentiometric heads in the confined deeper regional aquifer units. The potentiometric surface of the lower silty sandzone was likely above sea level prior to the start of regional pumping. Also, the vertical head gradient between the upper alluvial zone and the confined aquifer of the lower silty sand zone was probably quite low Nevertheless, the low overall permeability in the middle clayey zone has allowed heads in the upper alluvial zone to remain close to the surface despite the very significant head differences in the underlying aquifers.

The data in Figure 3-4 are derived from measurements taken in September, 1986 and depict a relatively uniform potentiometric gradient through the entire middle clayey zone. This suggests that the resistance to vertical groundwater flow across the middle clayey zone is reasonably consistent even though there is significant lithologic variability. This is not surprising as the average vertical permeability of the interbedded silt and clay units within the zone will tend to be dominated by the lower permeability clay units (Freeze and Cherry, 1979). However, the nature of the potentiometric variation with depth shown in Figure 3-4 suggests that the entire middle clayey zone acts as a very effective confining unit below the French Limited site and environs.

The water level fluctuations observed in piezometers completed in the middle of the middle clayey zone reflect the potentiometric response of these units within the middle clayey zone to imposed stresses on the geologic system. Stresses may be imposed naturally, for example, as a result of extensive blanket loads such as precipitation or changes in atmospheric pressure Stresses may also be induced artificially as a result of pumping from an aquifer unit above or below the middle clayey zone. Observations of water level fluctuations in the REI-P-10-2, and REI-P-10-4 piezometers monitoring the middle clayey zone during the aquifer testing program, described in more detail in AHA (1986), indicate no apparent response to changes in barometric pressure but rapid response to loadings induced by significant precipitation events (Figure 3-3). The precipitation-loading effect may be enhanced by the existence of numerous surface water bodies which may receive surface runoff during high precipitation events.

The significant response of the middle clayey zone to precipitation loadings was not anticipated prior to testing. The phenomenon is documented in the literature primarily in relation to blanket loads associated with tidal fluctuations (Dominico, 1972; Todd 1959). The lack of barometric response and the extremely efficient response to blanket precipitation loads can be explained by the presence of an extensive confining unit of very low permeability that prevents vertical drainage of pore water. A detailed explanation of the blanket precipitation load response is provided in AHA (1986).

3.3.2.2 Hydraulic Characteristics

The hydrogeologic characteristics of the middle clayey unit were analyzed by field and laboratory tests conducted during the 1986 field investigations (AHA, 1986). These investigations confirmed the generally low permeability of the clay and silt units and the lateral consistency of the zone in the vicinity of the French Limited site. The predominance of fine-grained materials and the observation of large potentiometric differences across the middle clayey zone also supported the conclusion that the zone is an effective barrier to downward migration of groundwater and acts as a confining layer for the underlying lower silty sand zone.

Slug tests were conducted on piezometers REI-P-10-3 and REI-P-10-4 during the 1986 field investigations. These piezometers are completed in clay strata in the middle of the middle clayey zone (see Figure 3-4) The slug tests were conducted by adding a known volume of water to raise the initial water level in each piezometer about 15 to 16 feet. The slug test response monitoring was conducted over a 30-day period. During this time Piezometer REI-P-10-3 recovered about 35 percent and piezometer REI-P-10-4 recovered about 28 percent. Semi-log plots were developed for analysis using both the method of Cooper and others (1967) and the method of Hvorslev (1951). These plots and analyses are provided in AHA (1986).

The hydraulic conductivity estimates using the two slug test analysis techniques are provided in Table 3-1. The substantial range in the estimates for piezometer REI-P-10-3 are the result of anomalous behavior in the response during the first 2000 minutes of the test. The anomalous response in the early portions of the test may be related to completion problems at this well or it may be the result of anomalous transducer readings. The hydraulic conductivity estimates derived from piezometer REI-P-10-4 are thought to be more reliable estimates for the clay in the vicinity of the piezometers.

Standard consolidation tests were also performed on three core samples of the clay strata in which piezometers REI-P-10-3 and REI-P-10-4 are completed to evaluate compressibility characteristics and intergranular hydraulic conductivities. The main purpose of the tests were to calculate specific storage (storage coefficient per vertical unit of aquifer thickness) values for the clay strata. The consolidation tests also provide an estimate of laboratory hydraulic conductivity for each core sample. The consolidation tests are described in AHA (1986). Calculated specific storage values varied from 2×10^{-6} to 4×10^{-6} cm^{-1} indicating a storage coefficient of 7.3×10^{-4} to 1.5×10^{-3} for the 12-foot (366-cm) thick stiff clay strata. The hydraulic conductivity values calculated from the consolidation tests ranged from 1.23×10^{-9} to 2.05×10^{-10} cm/sec -- a range typical of intergranular values for clays (Freeze and Cherry, 1979). The hydraulic conductivity values calculated from the consolidation tests are consistent with laboratory values calculated via the falling head permeameter tests reported by REI (1986a).

A field estimate of the vertical hydraulic conductivity of the portion of the middle clayey zone between piezometer REI-P-10-2 and the lower silty sand zone was determined from the response of this piezometer due to pumping well REI-10-1 completed in the lower silty sand zone (see Figure 3-3). Response was observed in piezometer REI-P-10-2 after about 7000 minutes of pumping well REI-10-1. A measurable response was not observed in piezometers REI-P-10-3 and REI-P-10-4 during the seven-day aquifer test.

The technique considered to be most appropriate to analyze the response in piezometer REI-P-10-2 is the ratio method described by Neuman and

TABLE 3-1

HYDRAULIC CONDUCTIVITY ESTIMATES FOR THE MIDDLE CLAYEY ZONE DERIVED FROM SLUG TEST RESPONSE DATA

TEST WELL	ANALYSIS METHOD	SELECTED TIME INTERVAL	ASSUMED COEF OF STORAGE	HYDRAULIC CONDUCTIVITY (CM/SEC)
P-10-3	Hvorslev	0-2000 minutes	-------	2.41×10^{-7}
P-10-3	Hvorslev	4000-40000 minutes	-------	8.92×10^{-9}
P-10-3	Cooper and others	1-1000 minutes	1.5×10^{-4}	1.09×10^{-6}
P-10-3	Cooper and others	3000-30000 minutes	1.5×10^{-5}	3.07×10^{-8}
P-10-4	Hvorslev	1-20000 minutes	-------	1.99×10^{-8}
P-10-4	Hvorslev	1-43000 minutes	-------	1.38×10^{-8}
P-10-4	Cooper and others	20-20000 minutes	1.5×10^{-5}	8.82×10^{-8}

Witherspoon (1972). Use of the method to determine vertical hydraulic conductivity is described in detail in AHA (1986). The method provides an estimate of the vertical diffusivity of the aquitard from the ratio of the drawdown response in the aquitard (s') and the drawdown response in the pumped aquifer (s) at time t after pumping starts. The vertical hydraulic conductivity of the aquitard, Kv, can be estimated from the vertical diffusivity provided the specific storage (S_s) is known.

Using specific storage values calculated from consolidation tests of core samples of the stiff clay strata as reasonable estimates for the storage characteristics of the middle clayey zone between piezometer REI-P-10-2 and the silty sand zone, the average vertical hydraulic conductivity for the middle clayey zone is calculated to be about $7x10^{-7}$ cm/sec. This value is considered to be conservatively high since the average specific storage of the tested interval is likely to be lower than that calculated for the clay strata because of the much greater vertical thickness of the tested interval.

Piezometers REI-P-10-3 and REI-P-10-4 did not appear to show a drawdown response due to pumping well REI-10-1 in the underlying silty sand zone. This is not surprising, since the underlying silt strata in which piezometer REI-P-10-2 is completed did not respond until about 7000 minutes into the test. The middle clayey zone has been referred to as an aquitard in the regional groundwater system. The analysis of the 1986 field tests indicates that the unit should more appropriately be referred to as an aquiclude because it is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.

Comparison of hydraulic conductivity values of the stiff clay estimated from field tests and laboratory tests indicates the field values are about two orders of magnitude higher. This is fairly typical since laboratory tests do not take into account secondary features such as slickensides and blocky structure which influence field hydraulic conductivity values The fact that this difference is apparent indicates that the field values are not significantly influenced by drilling effects during well completion. If smearing of fractures caused a significant "skin" effect, then field values would probably be closer to laboratory values. Vertical hydraulic conductivities rarely exceed horizontal conductivities but may be similar if vertical slickensides are a predominant influence on fluid flow. Consequently, the maximum vertical conductivity of the stiff clayey unit is thought to be about 10^{-7} cm/sec.

The potentiometric data provided in Figure 3-4 and the hydraulic conductivity of the unit relative to the hydraulic conductivities of the overlying upper alluvial zone and the underlying lower silty sand zone suggest that groundwater flow in the middle clayey zone is primarily downward under the prevailing vertical hydraulic gradient of about 1.0 ft/ft. The maximum groundwater flux (i.e., Darcy velocity) through the zone based on a maximum vertical hydraulic conductivities of 10^{-7} cm/sec is about $2.7x10^{-4}$ cubic feet per day per square foot ($2.05x10^{-3}$ gpd/ft^2 = 0.1 ft^3/yr/ft^2).

3.3.3 Upper Alluvial Zone

As noted in Section 2.2.3, the geologic information from a number of bore holes and cone penetrometer tests indicate a high degree of vertical and lateral grain-size variation within the upper alluvial zone which is typical of alluvial deposits. As is discussed below in Section 3.3.3.2, hydraulic conductivities are quite variable spatially as well as with depth within this zone. Despite this variation, it is reasonable to treat the upper alluvial zone as a single hydrogeologic unit in the vicinity of the French Limited site. The aquifer is unconfined but may display confined characteristics locally where significant clay lenses exist within the zone. The unit is recharged directly by precipitation and from surface runoff and ponds.

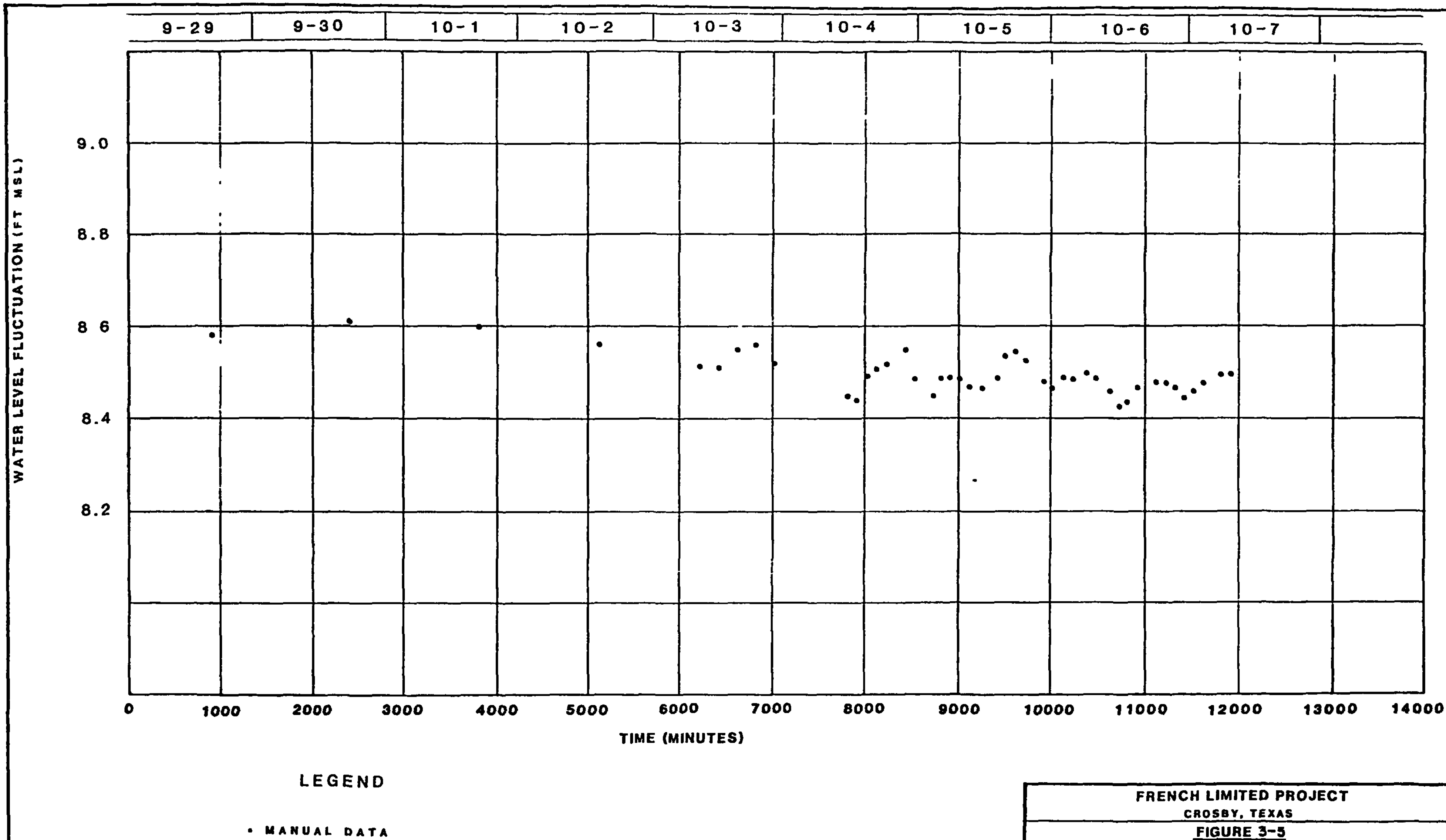
3.3.3.1 Water Level Interpretation

The water table occurs very close to ground surface in most areas of the site and is close to the water levels of the French Limited Lagoon and adjacent ponds. Water level fluctuations in wells completed in this zone respond to precipitation and evapotranspiration influences. These fluctuations have been documented in AHA (1986).

During the 1986 field investigations, water levels in the alluvial wells were observed to rise rapidly in response to the start of a precipitation event -- typically within 30 to 50 minutes. A lag time period of 200 to 500 minutes between the end of a precipitation event and the end of water level rise in the upper alluvial zone was observed in response to precipitation. A very similar precipitation response was observed during the 1988 pump testing program in the control wells monitored on August 10, 1988 prior to and during the test of well ERT-22 (see Appendix B) The increase in groundwater levels in the upper alluvial zone following significant precipitation events is believed to represent recharge to the zone both through direct infiltration and via surface water bodies.

The influence of evapotranspiration on alluvial groundwater levels is readily observable in the hydrographs of the upper alluvial zone wells during periods of little or no precipitation (Figures 3-5, 3-6, and 3-7). Water level drops of several hundredths of a foot are apparent in the alluvial wells between the night hours and the middle of the day, particularly on clear sunny days. Barometric influences are not apparent as would be expected for unconfined aquifer conditions. The influence of evapotranspiration on alluvial groundwater was not as consistent among the control wells monitored during the August, 1988 pump testing program as for the control wells monitored during the 1986 field investigation program. This is probably a result of the drought conditions during the summer of 1988 which resulted in groundwater levels being one to three feet below normal.

Potentiometric head variation with depth and stress response characteristics within the upper alluvial zone suggest that the interbedded clayey units within this zone do not significantly restrict vertical communication through the zone in the vicinity of the French Limited Lagoon. Wells completed at the basal sections of the upper alluvial zone at the REI-10 site have water levels very similar to the levels observed in wells



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CROSBY, TEXAS

FIGURE 3-5
WATER LEVEL RESPONSE PLOT

OBSERVATION WELL. REI 10-2 PUMPED WELL PRE-TEST
DATE(S) 9/29/86 to 10/7/86 COMMENTS

PROJECT No PR86-006	DATE 11-26-86	REVISION 1

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER, CO

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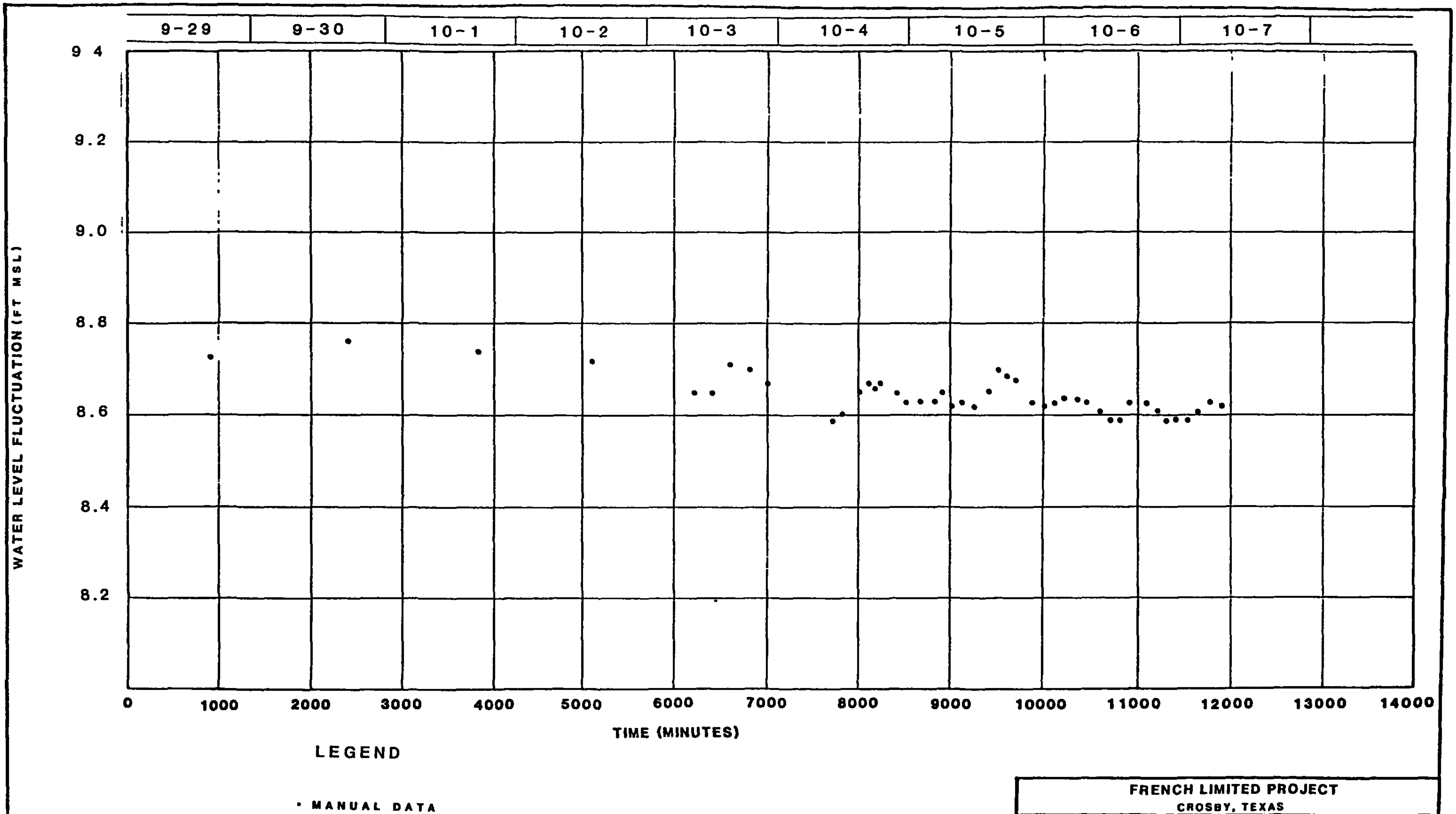


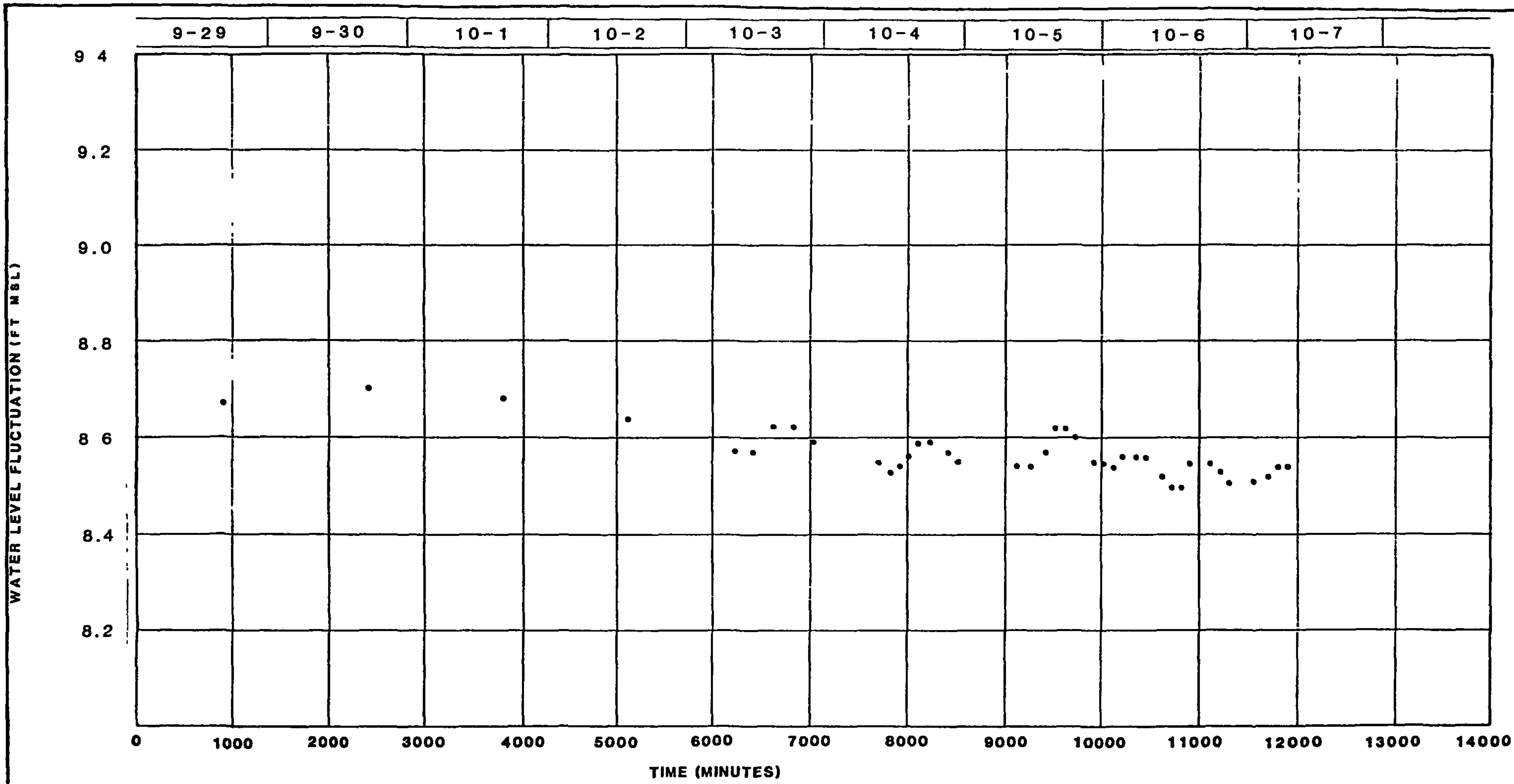
FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 3-6
WATER LEVEL RESPONSE PLOT

OBSERVATION WELL REI 10-3 PUMPED WELL PRE-TEST
DATE(S) 9/29/86 to 10/7/86 COMMENTS

PROJECT No PR86-006	DATE 11-26-86	REVISION 1

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER, CO.



LEGEND

• MANUAL DATA

FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 3-7
WATER LEVEL RESPONSE PLOT

OBSERVATION WELL. REI 10-4 PUMPED WELL PRE-TEST
DATE(S) 9/29/86 to 10/7/86 COMMENTS

PROJECT No PRFL-006	DATE 11-26-86	REVISION 1

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER, CO completed in the upper sections of this zone. Likewise, the basal wells respond to recharge and evapotranspiration influences in a manner similar (albeit damped) to wells completed in upper sections of the zone. These observations are consistent with the existence of reasonably good vertical communication within the upper alluvial zone at site REI-10.

The vertical hydraulic communication in the upper alluvial zone at the REI-3 site southeast of the South Pond is somewhat less than near the French Limited Lagoon at the REI-10 site. This is indicated by evidence of confined conditions at the base of the zone and the identification of significant clayey units within the zone. Observations of water level responses in the upper alluvial zone wells taken during the 1986 field investigation (AHA, 1986) yield insight into the vertical communication within this zone. The data, collected during the aquifer test of well REI-3-4, are provided in Figure 3-8. Diurnal fluctuations are most pronounced in well REI-3-3, the shallowest well completed in the upper alluvial zone at the REI-3 site. These fluctuations are damped in well REI-3-2, a well completed in the middle of the upper alluvial zone, and are further damped in well REI-3-1, the deepest well in this zone.

Water levels typically decline during the day in response to evapotranspiration, reaching a minimum level at about 8:00 PM, Central Daylight Time. These minimum levels are evident near the start of the test, about 1500 minutes into the test and about 4300 minutes into the test However, at 2900 minutes into the test on August 23, the water levels in the alluvium did not drop as expected from the diurnal pattern but continued to rise. This rise is due to precipitation and high relative humidity on this day.

Comparison of these water levels fluctuations with the relative humidity curve in Figure 3-8 show fairly good correlation. When relative humidities are below about 90 percent the water levels drop; above 90 percent the water levels appear to recover. The blanket precipitation loading response described in Section 3.3.2.1 does not appear in the alluvial wells because the lower alluvial zones are apparently not tightly confined. Instead there is a damped response in the deeper units within the upper alluvial zone in response to level changes in the water table as is reflected in the measurements from well REI-3-3.

These test results indicate relatively good communication between the sands in the upper alluvial zone despite the stratification indicated in the geologic cross sections. Consequently, it is reasonable to treat the upper alluvial zone as a single hydrologic unit. However, there may be locations within this zone where vertical communication is restricted by the clay strata.

Depth-to-water data for the upper alluvial zone are presented in Appendix C. The water level elevations for the upper alluvial zone presented in Appendix D have been calculated from the elevation and depth-to-water data of Appendix C. All data have been corrected to the well elevations surveyed in the summer of 1988 (ENSR, 1988b) for consistency. This correction accounts for discrepancies in elevation due to surveying differences but does not correct for the effects of subsidence. Subsidence would influence the elevations of the top of well casings and ground surface but would not

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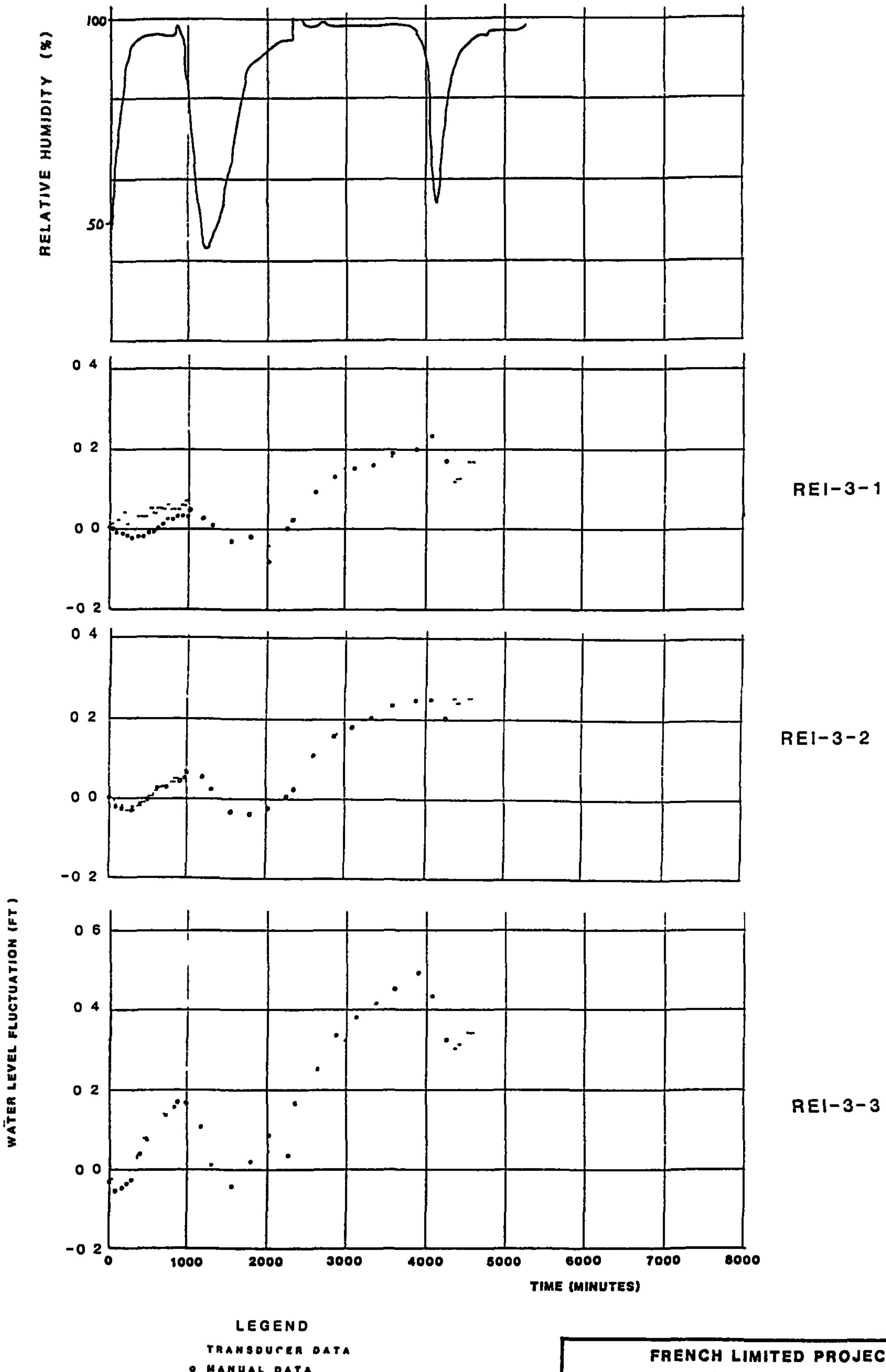

FRENCH LIMITED PROJECT
CROSBY, TEXAS

FIGURE 3-8

RESPONSE OF UPPER ALLUVIAL ZONE WELLS
DURING PUMP TEST OF REI-3-4 WELL
(8/21 to 8/25/86)

PROJECT No PRR6-006	DATE 11/25/86	REVISION 1

PREPARED BY APPLIED HYDROLOGY ASSOCIATES, DENVER CO

necessarily change the average groundwater elevation. From the water level elevation data of Appendix D, seasonal potentiometric surface maps (Plates 3 through 6) have been developed using data collected on days when many wells were measured.

The potentiometric surface map for the winter quarter (Plate 3) and the spring quarter (Plate 4) include historic data reported by LAN (1985) for similar dates in the winter and spring quarters of 1984; these data are included to extend the data base areally. The well locations and elevations of many of the wells monitored for the LAN (1985) report were not re-surveyed in 1988 and data from these wells are identified as approximate on Plates 3 and 4. Data collected at the surveyed wells in both 1984 and 1988 are depicted on these plates for a comparison of changes in water level elevations; generally, the water level elevations measured in 1984 and 1988 are within one foot. Historic data could not be used to extend the data base areally on Plates 5 and 6 because of significant declines in water level elevations in the summer and fall of 1988 due to the widespread drought which affected much of the U S. The data for the spring quarter (Plate 4) have the best areal distribution.

Plates 3 through 6 show that the potentiometric surface in the vicinity of the French Limited Lagoon generally follows the topography. There appears to be a groundwater divide to the north of the French Limited Lagoon in the vicinity of the swampy area surrounding U.S. Highway 90. This is not unexpected since surface water north of U.S. Highway 90 flows north and westerly towards the San Jacinto River (see Section 3 1) South of this divide groundwater flows at an average gradient of about 0 001 ft/ft toward the unnamed stream that is tributary to Rickett Lake. Immediately south of the French Limited Lagoon the groundwater gradient is about 0 006 to 0.008 ft/ft. This slight gradient away from the French Limited Lagoon suggests that recharge from the lagoon is at a very slow rate. The French Limited Lagoon and the various ponds about the site appear to recharge the groundwater system in the winter and spring quarters.

Groundwater from the topographically higher area upon which the Riverdale Subdivision is built flows easterly at a gradient of about 0.011 to 0 030 ft/ft toward the potentiometric and topographic low areas south of the French Limited Lagoon. Groundwater from the topographically higher areas to the east flow westerly at a gradient of about 0.002 ft/ft.

Evident in the potentiometric surface maps is that the water level elevations measured at wells ERT-30 and GW-2 are always lower than those in nearby wells. This is thought to be due to the absence of the higher permeability uncompacted and sandy S1 units in the vicinity of these wells causing water levels in these wells to equilibrate to those of lower interbedded (INT) units of the upper alluvial zone. The water level elevation at well REI-1 is always higher than in nearby wells. This is likely due to the fact that this well monitors only the upper eight feet of the upper alluvial zone. Also evident in the potentiometric surface maps is that the hydraulic gradient in the vicinity of wells ERT-23, ERT-27 and ERT-24 changes direction seasonally. This is thought to be a result of well ERT-23 monitoring five to seven feet less of the S1 sandy unit than wells ERT-24 and ERT-27 monitor because of its completion below the base of the abandoned Harris County landfill. Thus water levels in well ERT-23 appear to be representative of semi-confined strata in the interbedded (INT) unit and are less effected by the influences of precipitation and evapotranspiration.

The effect of the drought of the summer and fall of 1988 is quite apparent when Plates 4, 5, and 6 are compared. There was about two feet of water level decline between April and November at many of the wells. Hydrographs of a few select wells are presented in Appendix D; these also illustrate the effects of the drought.

3.3.3.2 Hydraulic Characteristics

Aquifer testing of the upper alluvial zone was completed in 1988 under the direction of Applied Hydrology Associates, Inc. Previous testing of the upper alluvial zone at the French Limited site and vicinity took place during the remedial investigations of the French Limited site performed by LAN (1985) and REI (1986a).

The results of the slug tests of seven upper alluvial zone wells conducted for the remedial investigation by LAN (1985) and the slug tests from four upper alluvial zone wells conducted during the remedial investigation by REI (1986a) are summarized in Table 3-2. These slug tests results should be used with considerable discretion not only because slug tests generally provide only order-of-magnitude results, but also because the raw data were not available to evaluate the interpretations. The pumping test results from REI (1986a) are not reported in Table 3-2 because of problems with the data and interpretations.

Well REI-3-3 was re-tested during the 1986 field investigations (REI, 1986b) in response to questions concerning the initial test reported by REI (1986a). The details of the re-test of well REI-3-3 are presented in AHA (1986). The results of this test have been included in Appendix A of this report and incorporated into the summary of hydraulic characteristics of the upper alluvial zone provided in Table 3-3.

Aquifer tests of the upper alluvial zone were performed in two stages in 1988 under direction of Applied Hydrology Associates Inc. Appendix B provides the detailed description and interpretation of the upper alluvial zone aquifer tests. Attachment 1 in Appendix B contains data from the preliminary short-term aquifer tests conducted on site between May 24 and May 26, 1988. Attachment 2 in Appendix B contains data from the longer term (6- to 8-hour) aquifer tests conducted between August 5 and August 15, 1988.

Table 3-3 summarizes the results of the preliminary and longer term aquifer tests. Only the results thought to be most representative for each aquifer test are summarized in Table 3-3. A comparison of the average hydraulic conductivity calculated from several aquifer tests to the sand-silt-clay percentages of the tested intervals (based on nearby cone penetrometer test data) is presented in Table 3-4. This comparison is provided to indicate the lithologic influence on the hydrologic characteristics of the aquifer test sites. The sand-silt-clay percentages at all the aquifer test sites could not be evaluated because of the lack of the detailed stratigraphic profiling that cone penetrometer tests provide.

TABLE 3-2

UPPER ALLUVIAL ZONE SLUG TEST RESULTS
FROM REMEDIAL INVESTIGATIONS

WELL NUMBER	SOURCE (SEE REFERENCES)	ANALYSIS METHOD	SANDPACK INTERVAL (ELEV. MSL-FT.)	HYDRAULIC CONDUCTIVITY (CM/SEC)
GW-2	REI, 1986a	Cooper and others	18.4 to -40.4	5.4×10^{-4}
GW-3	REI, 1986a	Bouwer and Rice	8.2 to -13.8	3.8×10^{-3}
GW-5	REI, 1986a	Bouwer and Rice	8.6 to -12.4	1.3×10^{-3}
GW-7	REI, 1986a	Bouwer and Rice	5.5 to - 6.5	2.3×10^{-3}
GW01	LAN, 1985	Bouwer and Rice	30.8 to - 7.2	3.7×10^{-3}
GW02	LAN, 1985	Cooper and others	-18.4 to -40.4	5.4×10^{-4}
GW03	LAN, 1985	Bouwer and Rice	-8.2 to -13.8	3.8×10^{-3}
GW04	LAN, 1985	Cooper and others	8.8 to -22.7	7.9×10^{-4}
GW05	LAN, 1985	Bouwer and Rice	8.6 to -12.4	1.3×10^{-3}
GW07	LAN, 1985	Bouwer and Rice	5.5 to - 6.5	2.3×10^{-3}

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TABLE 3-3

SUMMARY OF AQUIFER TEST DATA
FRENCH LIMITED SITE
CROSBY, TEXAS

PUMP WELL	OBS WELL	ANALYSIS METHOD	T GPD/FT	K CM/S	S	SATURATED SCREENED INTERVAL
ERT-10	ERT-9	Bursoy & Sommers (Recovery)	754	1 19X10^{-3}	0042	30 feet
ERT-10	REI-10-4	Boulton Del Yld	145	2 28X10^{-4}	00079	30 feet
ERT-20	ERT-20	Birsoy & Sommers (Recovery)	695	9 37X10^{-4}		35 feet
ERT-21	ERT-21	Theis Recovery	595	8 02X10-4		35 feet
ERT-22	ERT-22	Brisoy & Sommers (Recovery)	714	8 42X10^{-4}		40 feet
ERT-7	ERT-8	Theis Recovery	1387	2 33X10^{-3}	0041	28 feet
REI-3-3	REI-3-5	Boulton Del Yld	500	1 57X10^{-3}	003	15 feet
REI-10-2	REI-10-4	Boulton Del Yld	142	4 78X10^{-4}	0086	14 feet
REI-10-3	REI-10-3	Theis Recovery	4	1 88X10^{-5}		10 feet
ERT-23	ERT-23	Theis Recovery	8420	9.93X10^{-3}		40 feet
ERT-24	ERT-24	Theis Recovery	2922	3 94X10^{-3}		35 feet
ERT-25	ERT-25	Jacob Recovery	1550	1 83x10^{-3}		40 feet
ERT-26	ERT-26	Jacob Recovery	1260	1 49x10^{-3}		40 feet
ERT-27	ERT-27	Jacob Recovery	7000	8 25x10^{-3}		40 feet
ERT-28	ERT-28	Hvorslev Slug Test	52	4 8X10^{-5}		51 feet
ERT-30	ERT-30	Hvorslev Slug Test	63	7 43X10^{-5}		40 feet

TABLE 3-4

COMPARISON OF HYDRAULIC CONDUCTIVITY
AND LITHOLOGY AT AQUIFER TEST SITES

PUMPED WELL	OBS WELL	K (CM/S)	SCREENED INTERVAL (FT)	NEAREST CPT[1]	APPROXIMATE SCREENED INTERVAL %[2] SAND	SILT	CLAY
ERT-10	ERT-9	1.19×10^{-3}	22-52	C-5-85	47	16	37
ERT-10	REI-10-4	2.28×10^{-4}	35.2-48	C-5-85	31	14	55
ERT-7	ERT-8	2.33×10^{-3}	19.6-49.1	C-4-85	31	42	27
REI-3-3	REI-3-5	1.57×10^{-3}	6.5-22.3	C-1-85	63	12	25
REI-10-2	REI-10-4	4.78×10^{-4}	35.2-48	C-5-85	31	14	55
REI-10-3	REI-10-3	1.88×10^{-5}	37.7-48	C-5-85	29	13	58
ERT-23	ERT-23	9.93×10^{-5}	15-55	CPT-5	18	77	5
ERT-24	ERT-24	3.94×10^{-3}	10-45	CPT-3	29	62	9
ERT-26	ERT-26	1.49×10^{-3}	8-48	CPT-18	13	65	23
ERT-27	ERT-27	8.25×10^{-3}	8-48	CPT-14	33	55	13
ERT-28	ERT-28	4.8×10^{-5}	8-63	CPT-11	7	80	13

Notes:
1 Nearest cone penetrometer test within 100 feet of well (see Plate 1)
2 Sand = sand, silty sand, clayey sand
Silt = silt, sandy silt, clayey silt
Clay = clay, silty clay, sandy clay
Percent based upon interpretation of cone penetrometer test data presented in Supporting Data For Cross Sections and Fence Diagram in this report and REI (1986a).

Preliminary aquifer testing conducted at the French Limited site between May 24 and May 26, 1988 was coordinated with the monthly sampling of wells monitoring the upper alluvial zone in the vicinity of the French Limited site. The most reliable tests from the preliminary program are of two types. First, are the tests that were of short enough duration to be interpreted as slug tests. Second are the tests with specific capacities (i.e., the ratio of pumping rate to drawdown) high enough that pumping rate fluctuations and well bore storage effects were minimal beyond the first few minutes of these short-term tests

Wells ERT-28 and ERT-30 have very low yields thus making conventional pumping tests not possible. Wells ERT-28 and ERT-30 were pumped for only 4.25 minutes and two minutes respectively and were slow to recover. Slug test analyses of the recovery data measured at these wells (Attachment 2 in Appendix B) are thought to provide valid results which are listed in Table 3-3. The results should be viewed as order-of-magnitude estimates considering the limitations of slug test analyses. Slug test results are only representative of the zone immediately around the well bore -- a zone which may not be representative of the aquifer especially if the well was not thoroughly developed or if drilling smeared clays along the bore hole thus forming a "skin." However, it is notable that cone penetrometer test CPT-11, located near well ERT-28, indicated very little sand within the tested interval (Table 3-4) This supports the interpretation that the upper alluvial zone does have a low permeability in this area and that the low values of hydraulic conductivity calculated are not the result of poor well completions or test methodology.

The results from the short-term aquifer tests of wells ERT-23, ERT-24 and ERT-27 are representative of the approximate magnitude of transmissivities in the immediate vicinity of these wells because of the high specific capacity of these wells. The transmissivity and hydraulic conductivity estimates for these three wells are listed in Table 3-3.

The other results from the short-term aquifer test program are less reliable because of variable pumping rates and well bore storage effects Data from the recovery periods of the preliminary tests of wells ERT-25 and ERT-26 (Attachment 1 in Appendix B) are considered marginal but are thought to provide order-of-magnitude estimates of transmissivity and are therefore reported in Table 3-3.

The results of the longer term aquifer tests of wells ERT-20, ERT-21 and ERT-22 (Attachment 2 in Appendix B) all indicate similar values for transmissivity in the range from 595 to 714 gallons per day per foot (gpd/ft). Results from the drawdown analyses indicate a broader range for transmissivity but the recovery data are considered to be the most reliable and are therefore reported in Table 3-3. A slightly higher transmissivity estimate of 1387 gpd/ft was calculated for the longer term aquifer test of well ERT-7 which corresponds with the greater well yields observed at wells ERT-7 and ERT-8. A storage coefficient of 0.0041 was determined from the analysis of the recovery data at observation well ERT-8. This low value is representative of the early-test elastic storage coefficient as described by Neuman (1975) It is not representative of the specific yield that would characterize the storage coefficient for a long-term test or pumping program.

Transmissivity values appear to decrease toward the southwest corner of the French Limited Lagoon. The transmissivity calculated from the ERT-10 aquifer test is 754 gpd/ft at observation well ERT-9 and 145 gpd/ft at observation well REI-10-4. The storage coefficient of 0.0042 calculated at observation well ERT-9 is remarkably close to the estimate from the ERT-7 aquifer test while the storage coefficient calculated at observation well REI-10-4 was about half as large at 0.00079. The transmissivity values determined for the aquifer tests of nearby wells REI-10-2, REI-10-3 and REI-10-4 are even lower (Table 3-3). The relatively low average hydraulic conductivity values measured in this localized area is consistent with the high clay content noted in the tested intervals (37 to 88 percent) although the sand content is reasonably high (Table 3-4).

A more transmissive zone appears to exist in the vicinity of wells ERT-23 and ERT-27. This zone is localized as evidenced by the low transmissivity values calculated for wells REI-10-2 and REI-10-4 to the northeast and at wells ERT-28 and ERT-30 located to the southwest. The estimated transmissivity from the aquifer test of well ERT-23 is approximately 8400 gpd/ft. The recovery analysis of the data from well ERT-27 indicates a transmissivity of about 7000 gpd/ft; however, the results from well ERT-27 are considered to be less reliable because only a single pumping rate measurement was obtained during the short-term test. The high transmissivity observed at these two wells may be associated with a channel sand or point bar deposit in the upper alluvial zone This more transmissive zone does not appear to extend to the southeast as far as well REI-3-3 but may extend toward the northwest in the direction of well ERT-24 The preliminary test results at well ERT-24 suggest a transmissivity for this well of approximately 2900 gpd/ft The relatively high hydraulic conductivities calculated from the aquifer test data for wells ERT-23, ERT-27, and ERT-24 are consistent with the low clay content (five to 13 percent) and relatively high sand content (18 to 33 percent) at these sites (Table 3-4).

The data from a 12.5-hour aquifer test of well pair REI-3-3 and REI-3-5 (Appendix A) conducted during the 1986 hydrologic field studies appear to indicate delayed yield phenomenon and were therefore analyzed using the method of Boulton (1963). The calculated transmissivity is 500 gpd/ft. The calculated storage coefficient for the response during the early portion of the test was 0.003 which is similar to the values calculated for the ERT-10 and ERT-7 well tests.

Isopleths of the average hydraulic conductivity in the upper alluvial zone have been developed from the results presented in Tables 3-1, 3-2, and 3-3 and are illustrated on Plate 7. The results compare favorably with the soil vapor survey information (ENSR, 1988c). The extended lobe south of wells ERT-7 and ERT-8 appear to follow the areas of higher hydraulic conductivity around those wells. Likewise, the suppressed zone indicated in the soil vapor survey south of the wells at the REI-10 site appear to follow the area of lower hydraulic conductivity around these wells. The fairly uniform contours from the soil vapor survey over the rest of the area south of the

3.3.3.3 Groundwater Flow Rates

Groundwater flow rates and linear velocities are of interest because of their influence on migration rates of dissolved constituents which is discussed in Chapter 4.0.

Groundwater flow rates may be estimated on the basis of standard flow equations and reasonable ranges of hydraulic conductivity, hydraulic gradient and effective porosity within the zone of interest. Flow rates to the south of the French Limited Lagoon are of the most interest as they are directly related to potential constituent migration from the lagoon The average hydraulic conductivity of upper alluvial zone sediments to the south of the lagoon is in the range $8x10^{-4}$ to $2x10^{-3}$ cm/sec (Plate 7) Hydraulic conductivities of individual units within the upper alluvial zone will show a much broader range. However, average hydraulic conductivities within the upper alluvial zone are probably more representative for calculating groundwater flow rates due to the limited continuity of individual units within the zone. Maximum measured hydraulic gradients to the south of the lagoon range from 0.006 to 0 008 (Plate 5) The range of effective porosity within granular materials is probably within the range 0 1 to 0.3 (Freeze and Cherry, 1979).

Assuming maximum hydraulic gradients and a minimum average effective porosity of 0.1 for granular materials would yield the maximum average linear groundwater velocity in the range 50 to 165 feet per year. The high range of the calculated groundwater velocities is extreme as the effective porosity in the assumed transmissive sand units could be higher, in the range 0.2 to 0.3. In addition, the maximum measured hydraulic gradients south of the lagoon were used in the calculation which would also tend to overestimate the average flow velocity. Given these considerations, the average groundwater flow velocities south of the lagoon is in the range 50 to 100 feet per year. On this basis, groundwater advection distances over the past 20 years are likely 1000 to 2000 feet to the south of the French Limited Lagoon.

4.0 GROUNDWATER QUALITY AND CONSTITUENT TRANSPORT

This section attempts to integrate the hydrogeologic characterization described previously in Sections 2 and 3 with the observed distribution of organic constituents within the groundwater system.

4.1 CONTROLS ON ORGANIC CONCENTRATIONS IN GROUNDWATER

The existence of organic constituents in the shallow groundwater downgradient of the French Limited Lagoon has been attributed to leaching of organics associated with the lagoon sludge and underlying sediments. The rate of constituent migration within the groundwater of the upper alluvial zone is influenced by several factors. The primary factors include the physical and chemical properties of the constituents, natural degradation of the constituent in the groundwater, the nature and geometry of the source area, the rate and direction of groundwater flow, and the nature and variability of the aquifer materials. Each of these factors will be briefly described so that the reader will be able to follow the discussion of the data specific to the French Limited site.

4.1.1 Physical and Chemical Properties of Constituents

4 1 1 1 Miscibility and Solubility

Groundwater can act as a medium for the transport of chemical constituents if the constituents are miscible, i.e they readily mix with, or are soluble in water Immiscible liquids may also move through geologic materials and the prevailing hydrogeologic conditions influence their migration even though groundwater does not act as the transporting medium

The migration of miscible liquids is influenced directly by groundwater flow The solubility of a constituent controls the maximum concentration of that constituent in groundwater occurring at source areas, i.e. areas where the constituent might enter the groundwater system. Concentrations in groundwater generally tend to decrease away from source areas as a result of dilution and other processes. Source concentrations influence the concentrations observed in groundwater downgradient from a source area Constituents that are very soluble in water may achieve high concentrations in source areas if the source materials and mechanisms are available Consequently, the amount of the constituent that may be transported by groundwater (or the constituent loading) is potentially high. Of course, even constituents of low solubility are of concern if the constituent in question is not acceptable in very low concentrations.

The solubility of a number of organic constituents are listed in Table 4-1. It is important to note that these solubilities are measured in pure water and that actual solubilities in the groundwater of a particular area may be significantly different. In particular, certain organic constituents may be insoluble in pure water but have significant solubility in water containing high concentrations of organic solvents -- a situation which can occur near

TABLE 4-1

PHYSICAL, CHEMICAL AND ENVIRONMENTAL FATE PROPERTIES OF SELECTED CONSTITUENTS AT THE FRENCH LIMITED SITE

Constituent	Molecular Weight	Specific Gravity	Boiling Point (°C)[1]	Vapor Pressure (mm Hg)[2]	Water Solubility (mg/l)[2]	K_{oc} (ml/g)[3]	Log K_{ow} (ml/g)[4]	K_d[5]
Volatile Organics								
Benzene	78	0.8765	80.1	95.2	1750	83	2.12	0.11
Toluene	92	0.8669	111	28.1	535	300	2.73	0.60
1,2 Dichloroethane	99	1.2554	83.5	64	8520	14	1.48	
1,1,2 Trichloroethane	133	1.4416	114	30.0	4500	56	2.47	0.18
Vinyl Chloride	63	0.9195	-13.9	2660	2670	57	1.38	0.005
Base/Neutral Organics								
Bis(2-ethylhexyl)phthalate	391	0.9861	385	1.2	0.28		8.7	$6.6x10^{5}$
Di-n-butyl phthalate	278	1.048	340	$1\ 0\ x10^{-5}$	13	$1.7x10^{-5}$	5.6	
Napthalene	128	1.152	218	0.05	30		3.37	2.9
Pesticides and PCB's								
PCB 1242	266.5			$4.1\ x10^{-4}$	0.24		4.11	15.9
PCB 1254	328.4			$7.7\ x10^{-5}$	0.024		6.03	1320
Chlordane	406		175	$1.0\ x10^{-5}$	1.86		2 78	0.74
Dieldrin	381			$1.8\ x10^{-7}$	0.195		3.50	3.9

Notes

(1) Boiling Point at 760 mm Hg
(2) at 20-30°C
(3) Organic carbon partition coefficient
(4) Octanol-water partition coefficient
(5) Soil-water partition coefficient (LAN 1985)

source areas. As groundwater conditions and solvent concentrations may change dramatically within short distances of source areas, the solubility of certain constituents may also change. Decreasing solvent concentrations away from source areas can lead to constituents becoming less soluble and eventually becoming an immiscible phase that is deposited within the pore-spaces of the geologic materials. As long as solvent concentrations within the groundwater do not increase again at a later time, these deposited organic constituents are essentially immobile.

Immiscible liquids in groundwater have been termed "non-aqueous phase liquids" or NAPLs. Immiscible liquids that are less dense than water and will therefore tend to float on top of the water table are known as LNAPLs and are more commonly referred to as "floaters". As the water table forms an effective restriction to vertical migration of LNAPLs, the lateral migration of these liquids in geologic media tends to follow the configuration of the underlying water table. Immiscible liquids that are denser than water are known as DNAPLs or more commonly "sinkers". The migration of DNAPLs in subsurface geologic materials tends to be dominated by gravity and is influenced by the configuration of the geologic media rather than that of the water table. NAPLs are not presently observed in any samples drawn from the groundwater monitoring wells in the vicinity of the French Limited site. This indicates that migration of NAPLs is presently not significant.

Observation of relatively insoluble organic materials in bore hole samples immediately downgradient from the French Limited Lagoon suggests that NAPL migration may have occurred to a limited extent in the past. However, as explained above, the distribution of these materials may also be a result of groundwater transport in a miscible phase in the presence of organic solvents and subsequent deposition in the pore spaces of the geologic medium as solvent concentrations decreased away from the source area.

4.1.1.2 Constituent Partitioning

Chemical constituents often tend to favor one type of physical medium over another. Certain constituents tend to have a molecular affinity for a solid matrix (adsorption) rather than a liquid matrix (solution) and therefore tend to be relatively immobile in groundwater flow systems. Partitioning refers to the relative concentration of a constituent between two phases under equilibrium conditions. The soil-water partition coefficient, often given the symbol K_d, is the ratio of the concentration in the soil solid phase to the concentration in the water liquid phase. Low values of this coefficient indicate that the constituent tends to favor the water phase over the soil matrix and vice-versa.

Most volatile organic constituents tend to have an affinity for water rather than soil (i.e., K_d values will be less than unity). These volatiles are therefore quite mobile in groundwater as the soil will tend to adsorb only a small proportion of the constituent from the groundwater as it flows through the soil pores. As a result, the volatile organics tend to be the focus of most attention with respect to transport by groundwater. Most phthalates, poly-nuclear aromatics (PNAs), polychlorinated biphenols (PCBs) and heavy metals tend to have a strong affinity for soil matrices (K_d values much greater than unity). These constituents tend to become fixed in the soil and are essentially immobile in groundwater flow systems.

The equilibrium partition coefficient of a constituent is influenced by the nature of both the solid matrix and the liquid involved, by the concentration of the constituent, and by the initial distribution of the constituent. Many studies of these processes have indicated that increased organic carbon content and clay content in the solid matrix material will tend to increase the affinity of most organic constituents for the solid phase. This is the basis for carbon adsorption as a treatment method for groundwater contaminated with organic chemicals. For comparison of various constituents, a standard matrix is used for measurement of partition coefficients. Two common standard matrices are pure organic carbon and octanol. The octanol-water and carbon-water partition coefficients are given the symbols K_{ow} and K_{oc} respectively and the values are usually reported in a logarithmic format. The K_{oc} values are a reasonable measure of adsorption/desorption potential in a matrix containing a high organic carbon content. It can be seen from Table 4-1 that the ability of soils of high organic content to adsorb organic constituents might be two to three orders of magnitude greater than soils of low organic carbon content.

Typical values for K_{ow}, K_{oc} and K_d for several organic constituents are given in Table 4-1. The K_d values shown are for typical soils of low organic content. Direct measurement of adsorption/desorption characteristics of the upper alluvial zone materials at the French Limited site has not been performed The natural organic content of the shallow alluvial sediments is likely to be very low (less than one percent) so that the ability for these sediments to adsorb volatile organic constituents from the groundwater is low. The K_d values shown in Table 4-1 are probably representative of conditions in the sediments of the upper alluvial zone downgradient from the French Limited Lagoon.

Studies have also generally determined that solids will tend to attract (adsorb) organic constituents easier than they will release (desorb) them Consequently, the distribution coefficient for a constituent will tend to be lower under conditions of adsorption than under conditions of desorption. For relatively low concentrations in the liquid phase, the equilibrium partition coefficient for either adsorption or desorption conditions tends to remain constant and the partitioning is termed linear. At higher concentrations, the capacity for the solid matrix to adsorb and retain constituents tends to decrease so that the distribution coefficient becomes non-linear and a function of liquid concentration.

4.1.1.3 Volatility

The vapor pressure of a constituent is a measure of the ability of the constituent to volatilize into a gaseous phase. Volatilization of organic constituents from groundwater may occur particularly in unconfined aquifers where the unsaturated soil pore spaces above the water table are at atmospheric pressure. Volatilization of constituents will reduce dissolved concentrations of the constituent in the groundwater. The concentration of volatile organic constituents in soil gases may be a good indicator of concentrations within the underlying groundwater. Soil gas surveys have consequently become popular as a screening method for organic contamination of shallow groundwater.

4.1.2 Natural Degradation

Organic constituents in groundwater will tend to degrade with time due to natural biological and chemical processes that occur within the subsurface Biological degradation will eventually tend to break down the organic constituents into carbon dioxide and water although intermediate organic constituents (known as daughter products) may be created during the process The natural rate of degradation is usually limited by microbial populations which in turn are limited by environmental conditions such as oxygen content and availability of nutrients. Many studies (e g Barker and Patrick, 1985) have demonstrated the ability of natural biodegradation to limit the migration of organic constituents in groundwater, particularly in shallow unconfined groundwater systems where oxygen is available.

Rates of degradation for various organic constituents have been determined under a number of controlled conditions. As might be expected, organic constituents of low molecular weight tend to degrade easier than large organic molecules such as PCBs. Within groundwater systems, the rate of natural degradation is difficult to determine directly. Prediction of the influence of natural degradation on constituent concentrations in groundwater is often based on equations of exponential decay analogous to those predicting radioactive decay. Unfortunately, this is not a reliable predictive method as it does not consider the limiting condition imposed by oxygen or nutrient availability. In addition, the creation of daughter products during biodegradation may cause temporary increases of certain organic constituents.

4.1.3 Nature and Geometry of Source Area

Soil and sludge analyses from the French Limited site (LAN, 1985 and REI, 1986a) indicate that the concentrations of organic constituents in these units vary over a wide range. This might be expected at a site where disposal of highly variable petrochemical wastes occurred. Direct seepage of oily materials from the lagoon into the underlying sediments appears to have occurred as evidenced by core descriptions.

Leaching of organic constituents from the sludge and underlying sediments is considerably influenced by the organic carbon content of these source units. The French Limited Lagoon sludges contain high concentrations of volatile organic constituents. Desorption of volatile organic constituents such as benzene and vinyl chloride from the sludges tends to be difficult due to the high organic carbon content of the sludges and the high affinity of volatile organics for organic substrates. Core data indicate that the sludge zone has an organic carbon content between 30 percent and 60 percent (REI, 1986a). This reduces the ability for infiltrating waters to leach organic constituents from the sludge.

The organic content in the alluvial sediments immediately underlying the French Limited Lagoon is between two percent and six percent based on coring information (REI, 1986a). Desorption of volatile organics from the sediment matrix is considerably easier. Based on the data for several organic constituents summarized in Table 4-1, desorption of volatile organics from sediments containing low organic contents is likely to be 100 to 1,000 times easier than desorption from high organic content sludges. Consequently, it is likely that the affected alluvial sediments underlying the lagoon form the major source for the dissolved organics observed in the shallow groundwater downgradient from the lagoon.

4.1.4 Rate and Direction of Groundwater Flow

Dissolved constituents in groundwater will tend to move in the direction of predominant groundwater flow by the process of advection. Rates of constituent migration tend to be tracked on the basis of measurable concentrations of the constituent. Processes that tend to reduce constituent concentrations within a groundwater system have the effect of reducing the apparent rate of constituent migration. These processes include adsorption of the constituent on to the aquifer matrix, dispersion of constituents within the groundwater system, diffusion of constituents from relatively high permeability saturated zones to lower permeability saturated zones, degradation of constituents through biological processes or hydrolysis, volatilization, chemical precipitation, and dilution by mixing with unaffected waters. Lateral constituent migration within the upper alluvial zone will be primarily in the highest permeability units as these units form the most active groundwater flow zones. However, the rate of transport of these constituents may be considerably less than that of average groundwater flow velocities within these high permeability units due to the processes described above.

4.1.5 Nature and Variability of Aquifer Materials

The nature and variability of aquifer materials will influence the distribution of constituent concentrations within the groundwater In stratified geologic sediments, such as the upper alluvial zone at the French Limited site, there is significant variation in lithologic properties in the individual units. Average permeability of the individual clay, silt, and sand units varies over several orders of magnitude leading to a wide range of groundwater flow velocities within these units. The content of clay and organic carbon may also vary widely within the stratified units resulting in a large range of adsorption capabilities within the zone. Typically, units of high permeability and low clay content will occur adjacent to clayey units having low permeability but high adsorptive capabilities Groundwater preferentially flowing within the higher permeability units will also contact the adjacent clayey zones which will tend to adsorb organic constituents from the groundwater. Stratified zones with limited lateral continuity of individual units will tend to enhance mixing and dispersion of groundwater.

4.2 SHALLOW GROUNDWATER QUALITY

The evaluation of organic constituent distribution within the shallow groundwater in the vicinity of the French Limited site is based primarily on samples taken from a number of monitoring wells since studies at the site began in 1981. The location of monitoring wells at the site tends to be limited by access and is heavily weighted towards the margins of the French Limited Lagoon as many of the wells were installed to monitor water quality during the biodegradation demonstration performed in 1987 and 1988. Several of the monitoring wells installed during early studies of the site in 1983 and 1984 are no longer in existence.

Certain organic chemicals and heavy metals that have been detected in the sludge of the French Limited Lagoon are also detectable in the shallow groundwater close to the margins of the lagoon (LAN, 1985, REI, 1986a). Migration of constituents is restricted to the upper alluvial zone and the upper few feet of the underlying middle clayey zone.

4.2.1 Water Quality within Middle Clayey and Lower Silty-Sand Zones

The middle clayey zone underlying the upper alluvial zone forms an effective restriction to downward migration of organic constituents despite the existence of downward hydraulic gradients through this zone. This confining unit was the focus of extensive field studies to verify its effectiveness as a barrier to vertical contaminant migration (AHA, 1986; REI, 1986b) The zone is approximately 70 feet thick and only the upper few feet of the middle clayey zone appear to be influenced by migration of organic constituents based on observation of core samples and field readings of photo-ionization (HNu) meters. The extent of vertical migration of affected groundwater into the middle clayey zone is consistent with measured vertical permeabilities and vertical hydraulic gradients (AHA, 1986)

The first aquifer unit below the middle clayey zone has been informally termed the lower silty sand zone. Water quality samples from several wells installed in the lower silty sand zone confirm that no organic constituents have migrated through the middle clayey zone into this lower aquifer unit Initial indications of organics in groundwater samples from the GW-25 well completed in the lower silty sand zone (LAN, 1985) were shown to be due to poor well completion (AHA, 1986; REI, 1986b). The REI-10-1 well, completed in the same zone about 75 feet away from the GW-25 well, showed no evidence of organic constituents (REI, 1986b). The GW-25 well was drilled out and properly cemented in 1986 to prevent any further migration to the lower zone through this feature.

4.2.2 Water Quality within the Upper Alluvial Zone

Organic constituents occur in the groundwater of the upper alluvial zone. Generally, the highest concentrations of dissolved solutes occur around the margins of the lagoon. Certain organic constituents found in the sludges, such as PCBs, have not been detected in any groundwater samples due to the strong tendency of these chemicals to bind to solid matrices Concentrations tend to decrease downgradient from the lagoon in approximate accordance with the mobility of the various constituents. Most of the semi-volatiles, with the notable exception of napthalene, are not detectable in monitoring wells 150 to 200 feet downgradient from the lagoon. This reflects the generally low mobility of these constituents in groundwater due primarily to adsorption on the aquifer materials.

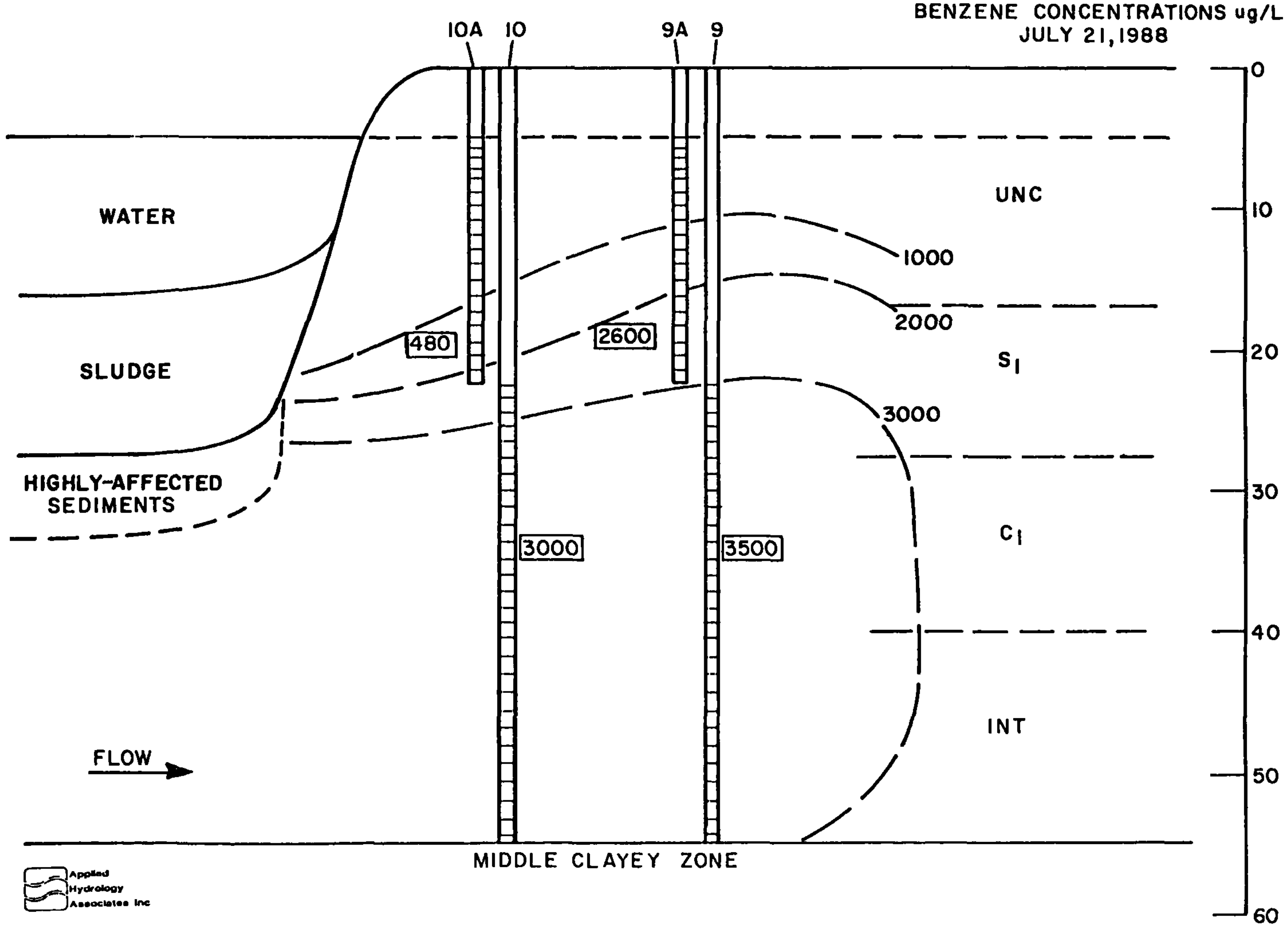
As discussed in section 4.1.1, the volatile organics such as benzene and vinyl chloride that are mobile in groundwater tend to be found in measurable concentrations at some distance from the presumed source area. Benzene and vinyl chloride distribution in groundwater show essentially the same pattern of migration, but vinyl chloride shows more temporal variability in individual wells. Due to their relatively high solubilities, mobilities and carcinogenic properties, both benzene and vinyl chloride have been identified as indicator parameters to be monitored in groundwater. In this report, benzene is selected as reasonably representative of mobile organic compounds in groundwater in the upper alluvial zone and is used to illustrate the spatial and temporal variation in concentration of these constituents in the vicinity of the site.

The measured benzene concentrations in monitoring wells over the period 1981 to 1988 are summarized in Plate 8. This plate illustrates the temporal variation in concentration at various locations in the vicinity of the site The present distribution of mobile organic constituents in the upper alluvial zone is represented by the average concentrations of benzene measured primarily during 1988 (Plate 9).

The geometry and nature of the source area tends to be the dominant control of dissolved organic concentrations in groundwater near the margins of the lagoon. As indicated in section 4.1.2, the high organic carbon content of the sludge materials in the French Limited Lagoon tends to impart a very high hydrophobic characteristic to organic compounds. Even though the sludges contain high concentrations of these organic constituents, desorption of these constituents directly from the sludge materials tends to be difficult. This would partially explain the very low organic concentrations noted in samples of the lagoon water (LAN, 1985, REI,1986). Core samples taken below the lagoon sludge layer indicates that oily liquids, presumably from disposal operations, have infiltrated directly into the underlying alluvial sediments. These sediments contain relatively low organic carbon contents (two to six percent) and would have much less tendency to chemically bind organic constituents It is therefore likely that the sediments directly below the lagoon, containing relatively high concentrations of organics, provide the major source for these constituents to enter the groundwater of the upper alluvial zone.

The wide range of organic content within the sludge and underlying sediments is reflected in the variability of organic concentrations in groundwater samples in close proximity to the lagoon. Groundwater concentrations probably vary both laterally and vertically in the stratified upper alluvial deposits near the source area as dispersive influences are limited. In areas downgradient from the lagoon, dispersion and other mixing processes will tend to reduce the vertical and lateral variability in groundwater concentration at any given location (Figure 4-1).

FIGURE 4-1
FRENCH LIMITED SITE
CONTAMINANT TRANSPORT NEAR LAGOON MARGIN



Water samples from monitoring wells screened through several feet of the alluvium essentially represent a composite of groundwater drawn from the stratified units at that location The concentrations in groundwater within the individual strata may differ considerably, particularly close to the lagoon source area. It can be seen from the data presented in Plate 8 that the composite groundwater concentration sampled from a monitoring well tapping these stratified units can also vary between sampling events despite all reasonable efforts to maintain consistency in sampling protocol. The temporal variation should tend to be most apparent in wells close to the lagoon For example, benzene concentrations tend to range widely both areally and temporally close to the lagoon, but are fairly consistent downgradient from the lagoon (Plate 8) Some of the temporal variations in wells close to the western part of the lagoon are attributable to operations during the bioremediation demonstration (ERT, 1987)

The bottom of the sludge layer in the French Limited Lagoon is approximately 25 to 30 feet below ground surface, or 20 to 25 feet below the average water table. Entry of organic constituents into the groundwater occurs primarily below this depth interval. This interpretation is supported by comparison of water quality data from twinned monitoring wells near the lagoon margins that are screened in the upper (approximately 5- to 20-foot depth) and lower (20- to 50- foot depth) parts of the alluvial deposits Benzene concentrations in the shallow wells (ERT-1A, 4A, 7A, 8A, 9A, 10A, and REI-6-2) are consistently lower than the corresponding deeper twinned monitoring wells (ERT-1, 4, 7, 8, 9, 10, and REI-6-1) as summarized in Plate 8 In addition it is notable that the concentrations in the shallow wells closest to the lagoon margin are generally less than shallow wells a few feet downgradient whereas the reverse is true in the deeper wells. This is shown in the results from well sites ERT-7,8 9 and 10 (Plate 8 and Figure 4-1), and illustrate the influence of dispersion within the upper alluvial aquifer away from the source zone below a 20-foot depth.

The distribution of mobile organic constituents in upper alluvial zone groundwater away from the immediate vicinity of the lagoon generally follows groundwater flow directions as determined from potentiometric data The potentiometric data base indicates that the general flow direction is to the south. The water quality data and the soil vapor survey support this interpretation (Plate 9).

The results of extensive groundwater quality monitoring between the French Limited Lagoon and Riverdale Subdivision, and in the Riverdale Subdivision itself, show no evidence of organic contamination in the subdivision wells that can be attributed to groundwater transport from the French Limited site (JEG, 1988). None of the mobile organic constituents that are typical of groundwater affected by the French Limited Lagoon, such as benzene, dichloroethane and vinyl chloride, are detectable in the Riverdale Subdivision wells. The occurrence of two phthalate compounds (bis(2-ethylhexyl) phthalate and di-n-octyl phthalate) in four of the Riverdale Subdivision wells is due to the use of PVC pipe and well casing (JEG, 1988) Both phthalates are used as plasticizers in the production of PVC products (Sittig, 1985). The phthalate compounds also have extremely low mobility in groundwater due to their high hydrophobic characteristics. For example, bis(2-ethylhexyl) phthalate is typically about one million times less mobile than benzene in groundwater (Table 4-1)

The western extent of detectable organic migration in the upper alluvial zone appears to be east of the line defined by wells ERT-23, 24, 27, 28, 29 and 30 (Plate 8). Samples from all these wells have not shown any detectable volatile organic constituents in numerous samplings during 1988 (Plates 8 and 9). Samples from the REI-5 well, screened within the disposal materials of the old Harris County landfill (Plate 8), show very low concentrations of benzene (3 and 6 ppb). These low levels of benzene are most likely attributable to leaching of landfill materials.

Sampling of five shallow monitoring wells located to the north of US Highway 90 did not indicate groundwater migration of organic constituents from the French Limited lagoon in this area (LAN, 1985) This is consistent with the general indication of groundwater flow below to the lagoon in a southward direction. To the east of the lagoon, the extent of groundwater contamination in the upper alluvial zone is constrained by the eastern margin of the alluvial deposits and the consistent indication of westerly groundwater flow gradients in this area.

Measurable concentrations of organic compounds are consistently found in monitoring wells ERT-20, 21 and 22 located some 200 feet south of the lagoon. Monitoring well GW-22, approximately 700 feet south of the lagoon showed no evidence of volatile organics based on samples taken in 1983 (LAN, 1985). A sample taken in 1984 from well REI-3-2, located just to the southeast of the South Pond and about 600 feet south of the French Limited Lagoon showed detectable concentrations of chloroform and 1,2 dichloroethane but no other volatile organics. Two other monitoring wells, REI-3-1 and REI-3-3 completed in different intervals within the upper alluvial zone at the same location did not show any detectable organic concentrations (REI, 1986a).

It is not clear whether the one sample from the REI-3-2 well represents groundwater migration from the French Limited Lagoon. It is possible that the black gelatinous liquid at the bottom of the South Pond could have influenced shallow groundwater quality at this location Chemical analyses of a bottom sample from the South Pond indicated the presence of benzene, napthalene and other organic compounds. The interpreted extent of detectable benzene in upper alluvial zone groundwater is shown in Plate 9. Also shown in Plate 9 are the summarized results of the soil vapor survey (ENSR, 1988). The interpretation of benzene concentrations is based, to some extent, on the results of the vapor survey.

In general, the areas of measurable volatile organic compounds in soil vapor correlate well with the shallow groundwater quality data from monitoring wells located about the French Limited site. It appears that fairly significant volatile concentrations in shallow groundwater, corresponding to at least 100 parts per billion (ppb) benzene, are required to generate measurable soil vapor concentrations in the overlying unsaturated zone. There are indications of elevated volatile organic concentrations in soil vapor noted in the vicinity of the line of monitoring wells ERT-27 to ERT-30 which show no detectable volatiles in groundwater (Plate 9). The soil vapor in this area does not appear to be related to groundwater quality and is more likely influenced by historic surface water flows along the drainage ditch in this location. Similarly, the isolated indication of elevated soil vapor concentrations in the southern part of the surveyed area (Plate 9) is more likely to be due to historic surface water flows along the unnamed stream in this location rather than elevated organic concentrations in the underlying groundwater.

The distribution of benzene in the upper alluvial zone groundwater as shown in Plate 9 would suggest a migration of this constituent of at least 500 feet to the south of the lagoon. Assuming that organic constituents first entered in the alluvial groundwater at the start of disposal operations at the French Limited site in 1966, the average migration rate to the south is about 20 to 25 feet per year. As indicated in section 3.3.3 3, groundwater flow rates to the south of the lagoon are probably in the range 50 to 100 feet per year and would indicate advection distances over the past 20 years of 1000 to 2000 feet. On this basis, the benzene migration distances appear to be 25 to 50 percent of that which would occur as a result of advection.

The lesser constituent migration rates compared with advective groundwater flow rates is reasonable as retardation and natural degradation processes will tend to attenuate the rate of constituent transport in groundwater. The stratified nature of the upper alluvial zone sediments and the limited continuity of individual units will enhance retardation processes. As a result, solute migration rates of mobile constituents will tend to approach advection rates based on average permeabilities rather than the highest permeability units.

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS OF HYDROGEOLOGIC CHARACTERIZATION

The major findings of the hydrogeologic characterization report are summarized below:

1) The upper stratigraphy of the French Limited site and environs can be divided into three zones These units are identified, from deep to shallow, as follows:

   Lower silty sand zone
   Middle clayey zone
   Upper alluvial zone

2) The lower silty sand zone is comprised of a poorly consolidated water-bearing silty sand or sandy silt directly underlying the middle clayey zone. This zone begins at a depth of approximately 109 to 137 feet below ground surface (elevation of -97 to -125 feet). This zone may represent a sandy zone within the Beaumont Formation or the upper part of the Montgomery Formation which underlies the Beaumont.

3) The lower silty sand zone is characterized as a confined aquifer unit having variable geologic and hydrogeologic properties in the area investigated. The average hydraulic conductivity of this zone measured during a 7-day pumping test ranges from a high value of about $4x10^{-3}$ cm/sec to a low of $1x10^{-3}$ cm/sec.

4) Potentiometric variation within the lower silty sand zone indicates a general eastward hydraulic gradient of about 0.001 ft/ft (6 3 ft/mile). The direction of the potentiometric gradient is thought to result from pumping of water supply wells near Barrett.

5) The middle clayey zone consists of 61 to 93 feet of thinly interbedded silty clays, clayey silts, and silty sandy clays of the Beaumont Formation. The top of the middle clayey zone occurs at about 43 to 55 feet below ground surface. The clays of the middle clayey zone are characteristically reddish-brown or blue-grey with reddish mottling, are blocky in texture and contain slickensides.

6) The middle clayey zone is an aquitard which isolates the groundwater of the upper alluvial zone from the lower silty sand zone. The zone is saturated but due to its clayey nature does not yield water easily to wells and tends to restrict the transmission of groundwater to adjacent aquifers. Well and piezometer data indicate a dramatic drop in potentiometric heads through the middle clayey zone. This drop in heads is equivalent to an average vertical hydraulic gradient of about 1.0 ft/ft. This confirms that the middle clayey zone provides substantial resistance to vertical groundwater flow through the unit.

7) Consolidation tests from cores indicate laboratory hydraulic conductivity values for clays of the middle clayey zone in the range $1.23x10^{-9}$ to $2.05x10^{-10}$ cm/sec. Slug tests on piezometers completed

within clay strata of this zone indicate field hydraulic conductivities in the range 10^{-6} to 10^{-7} cm/sec. A field estimate of the vertical hydraulic conductivity of the lower portion of the middle clayey zone was determined from the hydraulic response of the middle clayey zone to pumping the lower silty sand zone. The average vertical hydraulic conductivity for this unit is calculated at about 7×10^{-7} cm/sec. This value is considered to be conservatively high as a conservatively high value of specific storage was used to determine the hydraulic conductivity.

8) The upper alluvial zone consists of a stratified sequence of poorly consolidated sands, silty sands, gravels, and clay units. The alluvial materials were deposited in a now-abandoned river channel meander. The upper alluvial zone is up to approximately 55 feet thick and thins out to zero thickness at the eastern extent of the abandoned meander belt.

9) The geologic information from a number of bore holes and cone penetrometer tests indicates a high degree of vertical and lateral grain-size variation within the upper alluvial zone which is typical of alluvial deposits. However, the geologic interpretation suggests that the unit may be subdivided into four distinct strata which have appreciable lateral extent. The upper alluvial zone is mostly saturated and yields water to wells. The zone is considered as a single hydrogeologic unit due to the apparent good hydraulic communication within the unit. This is suggested by the similarity of potentiometric levels within the upper alluvial zone and the rapid response of monitoring wells completed at the base of the zone to influences affecting the near-surface water table. Spacial variation in hydraulic conductivities can generally be related to variation in grain size.

10) The upper alluvial aquifer is unconfined but may display confined characteristics locally where significant clay lenses exist within the zone. The unit is recharged directly by precipitation and from surface runoff and ponds Low permeability clayey and silt units within the zone tend to locally restrict vertical ground water movement.

11) The potentiometric surface within the upper alluvial zone in the vicinity of the French Limited Lagoon is quite flat. It appears that a groundwater divide may exist to the north of the French Limited Lagoon near U.S. Highway 90. South of the divide the potentiometric surface slopes at an average gradient of about 0.001 ft/ft toward the unnamed stream that is tributary to Rickett Lake. Immediately south of the French Limited Lagoon the groundwater gradient is about 0.006 to 0.008 ft/ft. The French Limited Lagoon and the various ponds about the site appear to recharge the groundwater system in the winter and spring quarters. Groundwater from the topographically higher area upon which the Riverdale Subdivision is built flows easterly at a gradient of about 0.01 ft/ft. Groundwater from the topographically higher areas to the east flow westerly at a gradient of about 0.002 ft/ft.

12) Results of slug tests and the very low yields of wells ERT-28 and ERT-30 indicate an area of relatively low average hydraulic conductivity within the upper alluvial zone between the French Limited Lagoon and the Riverdale Subdivision. Geologic information indicates very little sand within the tested intervals of these wells. This supports the interpretation that the upper alluvial zone does have a low permeability in this area and that the low values of hydraulic conductivity calculated are not the result of poor well completions or test methodology.

13) A more transmissive zone appears to exist in the vicinity of wells ERT-23 and ERT-27. This zone is localized as evidenced by the low transmissivity values calculated for wells REI-10-2 and REI-10-4 to the northeast and at wells ERT-28 and ERT-30 located to the southwest The estimated transmissivity from the aquifer test of well ERT-23 is approximately 8400 gpd/ft. The recovery analysis of the data from well ERT-27 indicates a transmissivity of about 7000 gpd/ft. The high transmissivity observed at these two wells may be associated with a channel sand or point bar deposit in the upper alluvial zone. This more transmissive zone may extend toward the northwest in the direction of well ERT-24. The short-term test results at well ERT-24 suggest a transmissivity for this well of approximately 2900 gpd/ft The relatively high hydraulic conductivities calculated from the aquifer test data for wells ERT-23, ERT-27, and ERT-24 are consistent with the low clay content (five to 13 percent) and relatively high sand content (18 to 33 percent) at these sites

14) The results of longer term aquifer tests of wells to the south of the French Limited Lagoon generally indicate values of transmissivity in the range from 600 to 1400 gpd/ft. Transmissivity values appear to decrease toward the southwest corner of the French Limited Lagoon. The transmissivity calculated from the ERT-10 aquifer test is 754 gpd/ft at observation well ERT-9 and 145 gpd/ft at observation well REI-10-4. The transmissivity values determined for the aquifer tests of nearby wells REI-10-2, REI-10-3 and REI-10-4 are even lower. The relatively low average hydraulic conductivity values measured in this localized area is consistent with the high clay content noted in the tested intervals (37 to 88 percent) although the sand content is reasonably high.

15) Isopleths of the average hydraulic conductivity in the upper alluvial zone developed from the results of pumping tests compare favorably with soil vapor survey information. Areas of higher average hydraulic conductivity appear to correlate with higher volatile organic concentrations in soil vapor.

16) The existence of organic constituents in the shallow groundwater downgradient of the French Limited Lagoon is attributed to leaching of organics associated with the lagoon sludge and underlying sediments. Leaching of organic constituents from the sludge and underlying sediments is considerably influenced by the organic carbon content of these source units. A high organic carbon content in the source matrix (between 30 percent and 60 percent) tends to increase its hydrophobic characteristics and reduces the ability of infiltrating

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waters to leach organic constituents from the matrix. The organic content in the alluvial sediments immediately underlying the French Limited Lagoon is between two percent and six percent based on coring information. Desorption of volatile organics from the sediment matrix is likely to be 100 to 1,000 times easier than desorption from high organic content sludges. Consequently, it is likely that the affected alluvial sediments underlying the lagoon form the major source for the dissolved organics observed in the shallow groundwater downgradient from the lagoon.

17) Migration of constituents is restricted to the upper alluvial zone and the upper few feet of the underlying middle clayey zone. The middle clayey zone underlying the upper alluvial zone forms an effective restriction to downward migration of organic constituents despite the existence of downward hydraulic gradients through this zone Only the upper few feet of the middle clayey zone are influenced by migration of organic constituents based on observation of core samples and field readings of photo-ionization (HNu) meters. The extent of vertical migration of affected groundwater into the middle clayey zone is consistent with measured vertical permeabilities and vertical hydraulic gradients. Water quality samples from several wells installed in the lower silty sand zone confirm that no organic constituents have migrated through the middle clayey zone into this lower aquifer unit. Initial indications of organics in groundwater samples from the GW-25 well completed in the lower silty sand zone were shown to be due to poor well completion. The REI-10-1 well, completed in the same zone about 75 feet away from the GW-25 well, showed no evidence of organic constituents. The GW-25 well was drilled out and properly cemented in 1986 to prevent any further migration to the lower zone through this feature.

18) The rate of constituent migration within the groundwater of the upper alluvial zone is influenced by several factors The primary factors include the physical and chemical properties of the constituents, natural degradation of constituents in groundwater, the nature and geometry of the source area, the rate and direction of groundwater flow, and the nature and variability of the aquifer materials Dissolved constituents in the upper alluvial zone tend to move in the direction of predominant groundwater flow by the process of advection Lateral constituent migration within the upper alluvial zone will be primarily in the highest permeability units as these units form the most active groundwater flow zones. However, the rate of transport of these constituents may be considerably less than that of average groundwater flow velocities within these high permeability units due to various processes that tend to reduce constituent migration rates These processes include adsorption of the constituent on to the aquifer matrix, dispersion of constituents within the groundwater system, diffusion of constituents from relatively high permeability saturated zones to lower permeability saturated zones, degradation of constituents through biological processes or hydrolysis, volatilization, chemical precipitation, and dilution by mixing with unaffected waters.

19) Generally, the highest concentrations of dissolved solutes occur around the margins of the lagoon. Certain organic constituents found in the sludges, such as PCBs, have not been detected in any groundwater samples due to the strong tendency of these chemicals to bind to solid matrices. Concentrations tend to decrease downgradient from the lagoon in approximate accordance with the mobility of the various constituents. Most of the semi-volatiles, with the notable exception of napthalene, are not detectable in monitoring wells 150 to 200 feet downgradient from the lagoon. This reflects the generally low mobility of these constituents in groundwater due primarily to adsorption on the aquifer materials.

20) The volatile organics such as benzene and vinyl chloride that are mobile in groundwater tend to be found in measurable concentrations at some distance from the presumed source area. Benzene and vinyl chloride distribution in groundwater show essentially the same pattern of migration, but vinyl chloride shows more temporal variability in individual wells. Due to their relatively high solubilities, mobilities and carcinogenic properties, both benzene and vinyl chloride have been identified as indicator parameters to be monitored in groundwater. In this report, benzene has been selected as reasonably representative of mobile organic compounds in groundwater in the upper alluvial zone and has been used to illustrate the spatial and temporal variation in concentration of these constituents in the vicinity of the site

21) Generally the areas of measurable volatile organics in soil vapor correlate well with shallow groundwater quality data from monitoring wells. It appears that fairly significant volatile concentrations in shallow groundwater, corresponding to at least 100 parts per billion benzene, are required to generate measurable soil vapor concentrations in the overlying unsaturated zone.

22) The western extent of detectable organic migration in the upper alluvial zone appears to be east of the line defined by wells ERT-23, 24, 27, 28, 29 and 30. Samples from all these wells have not shown any detectable volatile organic constituents in numerous samplings during 1988. Samples from the REI-5 well, screened within the disposal materials of the old Harris County landfill, show very low concentrations of benzene (three and six parts per billion). These low levels of benzene are most likely attributable to leaching of landfill materials.

23) The results of extensive groundwater quality monitoring between the French Limited Lagoon and the Riverdale Subdivision, and in the Riverdale Subdivision itself, show no evidence of organic contamination in subdivision wells that can be attributed to groundwater transport from the French Limited site (Jacobs Engineering Group, 1988). Potentiometric data indicate gradients from the Riverdale Subdivision toward the potentiometric and topographic low areas south of the French Limited Lagoon. Furthermore, none of the mobile organic constituents that are typical of groundwater affected by the French Limited Lagoon, such as benzene, trichloroethane and vinyl chloride, are detectable in the Riverdale Subdivision wells.

The occurrence of two phthalate compounds (bis(2-ethylhexyl) phthalate and di-n-octyl phthalate) in four of the Riverdale Subdivision wells is interpreted as being due to PVC pipe and well casing as both phthalates are used as plasticizers in the production of PVC products. The phthalate compounds also have extremely low mobility in groundwater due to their high hydrophobic characteristics. For example, bis(2-ethylhexyl) phthalate is typically about one million times less mobile than benzene in groundwater.

24) Sampling of five shallow monitoring wells located to the north of US Highway 90 did not indicate groundwater migration of organic constituents from the French Limited lagoon in this area. This is consistent with the general indication of groundwater flow below to the lagoon in a southward direction. To the east of the lagoon, the extent of groundwater contamination in the upper alluvial zone is constrained by the eastern margin of the alluvial deposits and the consistent indication of westerly groundwater flow gradients in this area. Measurable concentrations of organic compounds are consistently found in monitoring wells located some 200 feet south of the lagoon. A monitoring well located approximately 700 feet south of the lagoon showed no evidence of volatile organics based on samples taken in 1983. It is not clear whether low levels of volatile organics detected in a single sample from a well, located just to the southeast of the South Pond and about 600 feet south of the French Limited Lagoon represents groundwater migration from the French Limited Lagoon. It is possible that the black gelatinous liquid at the bottom of the South Pond could have influenced shallow groundwater quality at this location.

25) The distribution of benzene in the upper alluvial zone groundwater would suggest a migration of this constituent of at least 500 feet to the south of the lagoon. Groundwater flow rate calculations indicate advection distances over past 20 years of 1000 to 2000 feet. Thus retardation processes have effectively reduced the rate of migration of benzene -- one of the most mobile organic constituents. The stratified nature of the upper alluvial zone sediments and the limited continuity of individual units will enhance retardation processes As a result, solute migration rates of mobile constituents will tend to approach advection rates based on average permeabilities rather than the highest permeability units

5.2 IMPLICATIONS FOR GROUNDWATER REMEDIAL ACTION

The hydrogeologic characterization of the site supports groundwater withdrawal and treatment as a basic, viable remedial action for the upper alluvial zone at the French Limited site. In specific areas, this basic remedial option may be complimented by additional active measures and by natural processes in order to achieve clean-up objectives for the groundwater in an environmentally acceptable manner and within a reasonable time-frame. The characterization serves as a basis for design of the groundwater withdrawal system; highlights conditions that will influence clean-up efficiency; and identifies a few areas of additional data requirements to refine the design. Recommendations for additional data will be discussed in section 5.3.

The groundwater remedial system should address two basic areas to control contamination in the upper alluvial zone associated with the site: near-source control and migration control. Near-source control refers to remedial activities associated with groundwater and aquifer materials below, and in the immediate vicinity of, the French Limited Lagoon Migration control refers to remedial activities associated primarily with groundwater that has migrated beyond the site boundaries and contains relatively mobile volatile and semi-volatile organic constituents

5.2.1 **Near-Source Control**

The near-source control area may be considered to lie within 200 feet of the lagoon margin and north of Gulf Pump Road. Dissolved benzene concentrations in the groundwater typically range from 2000 to 5000 ug/l in this area (Plates 8 and 9). The characterization report confirms previous investigation findings that the highest concentrations of organic constituents exist in the groundwater and associated aquifer materials in the immediate vicinity of the lagoon In addition to the relatively mobile volatile and semi-volatile organic constituents that are also found in groundwater downgradient of the lagoon, less-mobile organic and inorganic constituents are present.

The upper alluvial zone materials in the first few feet directly below the lagoon base have been directly affected by infiltration of liquid wastes and leachates from the lagoon. These materials will be remediated using enhanced biodegradation processes as part of the lagoon clean-up program. The bioremediation demonstration program (ERT, 1988) indicated that additional release of organics into the adjacent shallow groundwater may temporarily occur as a result of reducing the hydrophobic character of the lagoon sludge.

The existing contamination in the groundwater and native aquifer materials in the upper alluvial zone will be remedied primarily by groundwater withdrawal and treatment. This system will also remedy any additional organic releases into the upper alluvial zone resulting from the bioremediation process. Withdrawal of groundwater in the vicinity of the lagoon will locally reverse the hydraulic gradient thus inducing groundwater flow back towards the lagoon. This will tend to draw back contaminated groundwater that has migrated away from the lagoon and prevent any further migration of contaminated groundwater.

Removal of organic constituents from the aquifer materials will be accomplished indirectly by reducing concentrations in the groundwater and thus inducing constituents to desorb from the aquifer materials. The discussion on constituent migration in section 4 1 of this report indicates the relative efficiency of removal of constituents from the aquifer materials in this manner. For constituents that have a strong affinity for a solid matrix and are essentially immobile in groundwater (i.e K_d factors greater than 10) this method is extremely inefficient. However, because of their immobility in groundwater, removal of these constituents from the solid matrix of the aquifer is not of great concern. Removal of mobile constituents (i.e. K_d factors less than 1), such as benzene and vinyl chloride, should be relatively efficient as these constituents exist almost entirely in the water phase and have a low affinity for the aquifer matrix except if there is a high organic content.

The constituents that may prove to be relatively inefficient to remove by conventional groundwater pumping are the less-mobile constituents that tend to desorb from soils fairly slowly. These constituents have a stronger affinity for a solid matrix than water (i.e K_d factors between 1 and 10), and include many of the semi-volatile organics such as napthaline In almost all cases, constituents tend to more readily adsorb to soils than they desorb, so that even for relatively mobile constituents it will generally require pumping of several pore volumes to remove the constituent from the soils by groundwater flushing.

The characterization study indicates that, near the lagoon margins, the highest organic concentrations in groundwater are found in the lower part of the upper alluvial zone (C1 and INT units). The upper part of this zone (UNC and S1 units), have lower organic concentrations as they are largely above the main source area -- the base of the lagoon sludge and underlying soils. Withdrawal systems should be designed to remove the groundwater at the points of highest contaminant concentration. This maximizes efficiency of treatment and minimizes the migration of contaminants into zones that possibly have lower concentrations. Recognizing this fact, groundwater withdrawal wells near the lagoon margins should be screened in both intervals within the upper alluvial zone to maximize efficiency of removal of high concentration groundwater.

The drawdown of water levels associated with a groundwater withdrawal system may result in a significant unsaturated zone above the zone of active groundwater flow. This unsaturated zone may contain elevated organic concentrations in pore waters or soils that would not be flushed directly by groundwater. Flushing of these zones will be limited to infiltrating water from surface water bodies or precipitation. This situation may be addressed in several ways. For example, pumping could periodically be curtailed to allow water levels to rise and flush the unsaturated zone or the pumping could be combined with reinjection of clean water into shallow zones Removal of volatile and semi-volatile constituents from the unsaturated zone could be enhanced, if necessary, by combining groundwater pumping with induced soil venting using vacuum extraction pumps.

5.2.2 Migration Control

The migration control area may be considered to approximately coincide with the area south of Gulf Pump Road which has benzene concentrations in the groundwater in excess of 5 ug/l (Plate 9). Concentrations of dissolved benzene in this area range from 5 to 2000 ug/l (Plate 9). The dissolved organic constituents in the groundwater of the upper alluvial zone in the migration area are relatively mobile volatile and semi-volatile compounds. Considering the type of constituents involved, a basic groundwater withdrawal system should be a fairly efficient method of groundwater remediation in this area. The major difficulty with this type of remedial system is removal of volatile organic constituents that have migrated into the relatively low permeability clay and silt units of the upper alluvial zone and the upper part of the middle clayey zone.

The characterization study indicates that the northern, eastern, and southern extent of organic migration needs to be defined in a little more detail to finalize the optimum placement of withdrawal wells. The withdrawal system needs to be designed so that it works in conjunction with the near-source control system and minimizes additional migration of contaminated groundwater.

The progress of the groundwater clean-up will be tracked by routine monitoring of groundwater quality. This monitoring will be used to assess whether enhancement of the basic groundwater withdrawal scheme is necessary in order to meet clean-up time frames. Enhancement options that may be considered include reinjection of clean water to increase the rate of groundwater movement towards withdrawal wells, in-situ bioremediation, vacuum extraction, and alkali-polymer injection.

5.3 RECOMMENDATIONS

The following recommendations are made to obtain the remaining data necessary to finalize the design of the groundwater remediation system for the French Limited site. Several of these recommendations have resulted directly from the detailed evaluation of data in this characterization study. Other data requirements were previously recognized and have been refined as a result of the study.

1) Better define the southern, northern, and eastern extent of organic migration in the upper alluvial zone groundwater by sampling of existing wells and proposed wells. To the south, the REI-3 well nest should be sampled on a regular basis, and an additional five to eight monitoring wells located to the west, south and east of the South Pond should be installed It is recommended that four to five initial wells should be completed approximately 200 feet downgradient (south) of the proven extent of groundwater contamination based on existing well sampling and soil vapor results. The well locations should follow the apparent higher permeability trends indicated by the results of the soil vapor survey The location of additional wells will be dependant on the results of field monitoring and confirmatory sampling of these initial wells and existing wells. These results will be evaluated to determine whether the extent of contaminant migration is adequately defined.

   The northern and eastern extent of organic migration in the upper alluvial zone groundwater should be better defined by sampling of existing wells REI 12-2 and GW-13, and installation of two additional well sites -- one located in the extreme northeast of the French Limited site and a second located along Gulf Pumping Station Loop Road near FG5 (see Plate 1)..

2) Selected well locations should have two monitoring wells screened in the upper (UNC and S1 units) and lower (C1 and INT units) to evaluate vertical variation in groundwater concentrations at locations downgradient from the lagoon. This information will be used to determine whether fully screened or partially screened withdrawal wells are optimal in the migration control area.

3) The sediments at the base of the South Pond should be sampled at several locations for analysis of constituents on the EPA target compound list (TCL). This is necessary to confirm whether these sediments will influence groundwater cleanup adjacent to the South Pond.

4) Water samples should be collected for TCL analysis at several locations along the northern margin of the South Pond to determine whether contaminated groundwater south of the French Limited Lagoon is migrating into the pond.

5) A series of controlled batch mixing or leaching tests of contaminated soil samples with site groundwater should be undertaken to evaluate the ability of groundwater flushing to remove certain organic constituents from the soil. It is recommended that these tests be performed on samples collected during a planned subsurface drilling program focused on more closely defining the distribution of aromatic hydrocarbons near the lagoon margins.

6) Seasonal (quarterly) monitoring of water quality and water levels should continue. The focus should be more on site-wide monitoring rather than near-lagoon monitoring. The proposed new monitoring well locations will greatly enhance the site-wide coverage

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BOOKMARK

ATTACHMENT A

DEFINITIONS AND BASIC PRINCIPLES

Groundwater flows through a porous media under the influence, or driving force, of a *hydraulic gradient*. The hydraulic gradient is defined as the change in potentiometric head over the distance measured in the direction of flow.

$$I = dh/dl \quad \text{(1)}$$

where: I = hydraulic gradient [dimensionless]
dh = potentiometric head change [L]
dl = distance measured along flow path [L]

The hydraulic gradient is a dimensionless ratio and is usually expressed as a unitless number or in feet per mile.

The rate of groundwater flow through a porous media is usually expressed in terms of a *specific discharge* or volume of flow per unit time per unit cross-sectional area. Specific discharge has been found to be proportional to the hydraulic gradient and the constant of proportionality, which is a measure of the resistance of the medium to groundwater flow, is known as the *hydraulic conductivity*.

The terms defined above are related in the simple flow equation.

$$q = Q/A = KI \quad \text{(2a)}$$

or:

$$Q = KIA \quad \text{(2b)}$$

where: q = specific discharge [L/T]
Q = volume of flow per unit time [L^3/T]
A = cross-sectional area of flow [L^2]
K = hydraulic conductivity [L/T]
I = hydraulic gradient [dimensionless]

The hydraulic conductivity is a function of both the media and the fluid flowing through it. It is related, but not synonymous with the more fundamental property known as the *permeability* which is a function only of the porous media. As the fluid of interest in most groundwater situations is water, the hydraulic conductivity is more commonly used.

The specific discharge has dimensions of velocity. It is important to recognize, however, that the specific discharge is not a measure of the average linear groundwater flow velocity. Groundwater flows through the open spaces (pores or fractures) within the media. The actual cross-sectional area available for groundwater flow is therefore related to the proportion of open space that is effective in allowing the transmission of flow. This fraction is referred to as the *effective porosity*. The *average linear velocity* of groundwater flow is of interest in solute transport calculations as it influences the rate of solute migration. The specific discharge is also of interest as this influences the

469492

amount or mass of solute migration. The average linear velocity of groundwater flow may be expressed by the equation:

$$v = q/n \quad \text{.......................................(3a)}$$

or: $$v = KI/n \quad \text{.......................................(3b)}$$

where: v = linear flow velocity [L/T]
q = specific discharge [L/T]
n = effective porosity [dimensionless]

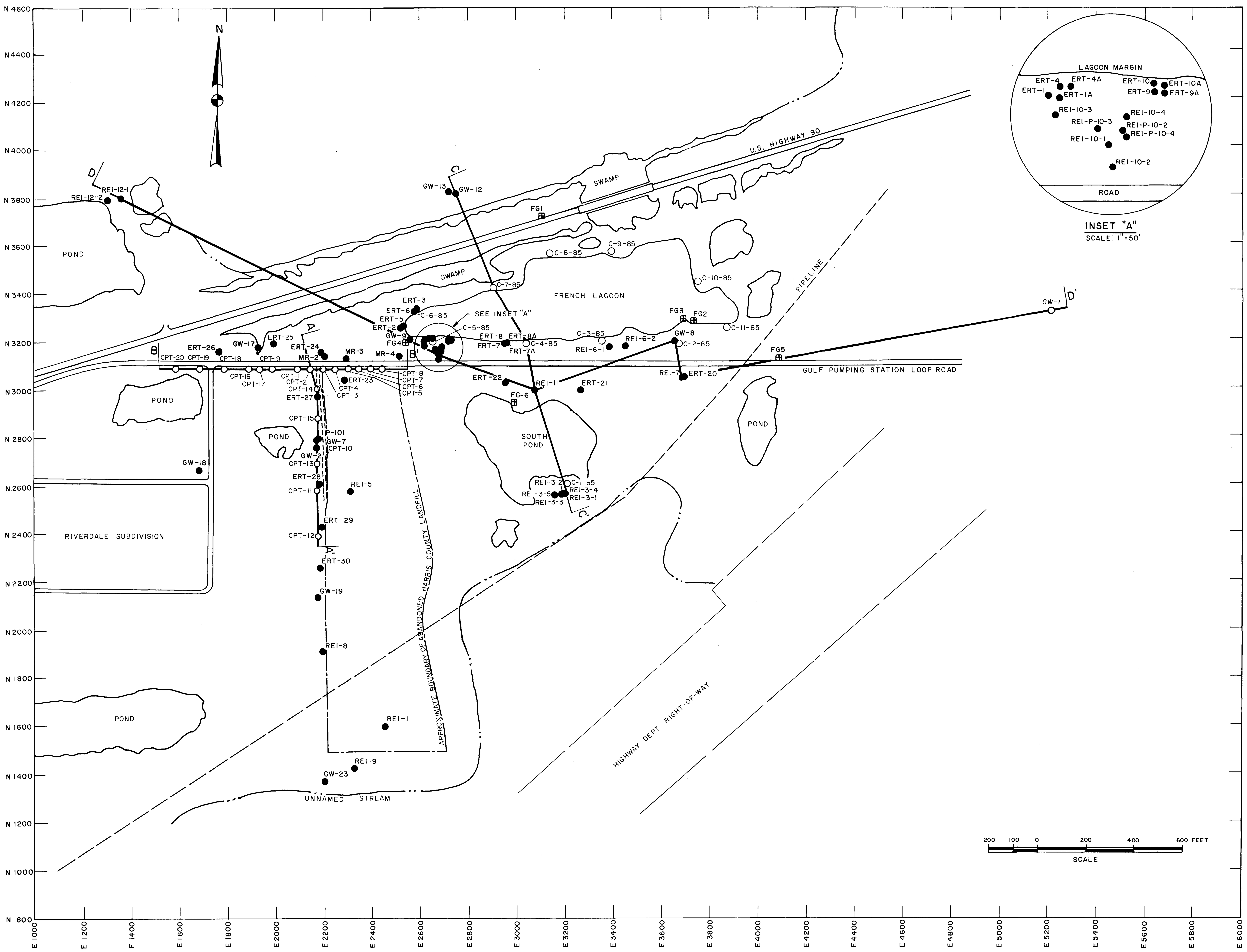
It may be seen from equation (3) that the effective porosity has a large influence on the linear velocity. If groundwater flow is primarily through the pore spaces of a geologic material, then the effective porosity is similar to the actual porosity that may be estimated from laboratory measurements on core samples. If flow is through interconnected fractures or other secondary features within the geologic material, then the effective porosity may be much smaller and average linear velocities much higher. However, it must be recognized that interactions between groundwater in the fractures and porewater in the matrix will influence the rate of solute transport through the media. Fracture-matrix interaction is particularly important in low permeability units such as clays where rates of groundwater flow are very low. In such situations, the matrix porosity tends to dominate the rate of solute transport even though the primary groundwater flow paths may be through the fractures.

The hydrologic characteristics of geologic units may be estimated on the basis of field tests or laboratory tests on core samples Field tests are less controllable than laboratory tests but have the advantage of measuring the insitu properties of the material. For example, core samples of a fractured material may not contain a representative density of fractures Consequently, laboratory measurements of hydrologic properties such as hydraulic conductivity may not be representative of insitu conditions.

Field tests usually involve the measurement of pressure response to an imposed stress such as pressure reduction due to pumping. The transient response of a geologic unit to a change in pressure is influenced by both the hydraulic conductivity and the *specific storage* of the unit. The specific storage is defined as the volume of water released from a unit volume of the material under a unit decline in head. The dimensions for this property are therefore L^{-1}. For saturated groundwater flow conditions, the release of water under a declining head is caused primarily by compaction of the saturated material. The specific storage is thus directly related to the *compressibility* of the material.

The insitu hydraulic conductivity of clay may be underestimated on the basis of laboratory tests on cores which will tend to reflect values for the clay matrix. Similarly, consolidation tests on core samples will tend to reflect the compressibility characteristics of the clay matrix, not that of the secondary features. Consequently, values for specific storage of the clay that are calculated from consolidation tests of cores, are representative of the clay matrix. The secondary features typically only constitute a small fraction of the clay volume. The fractures and slickensides are very compressible but, in terms of the bulk volume, they impart a very small

060494



LEGEND

FG1 ⊞ FLOOD GAUGE LOCATION

GW-2 ● WELL LOCATION

○ CONE PENETROMETER TEST

X——X' LOCATION OF CROSS SECTIONS

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001
MASTER MONITOR WELL LOCATION MAP
FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

PLATE I

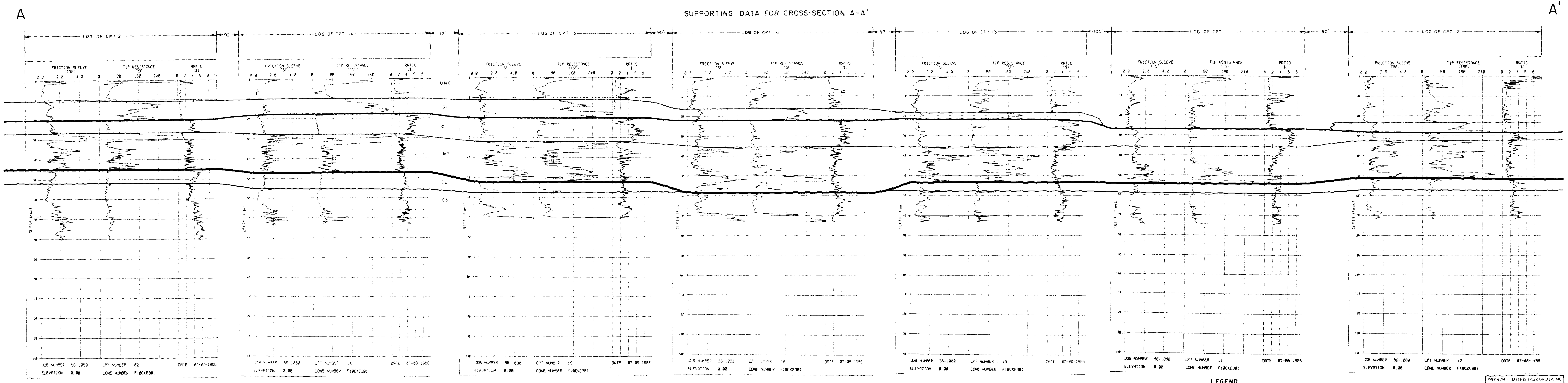
SITE AND CROSS-SECTION LOCATION

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26				
DATE	REVISION	DRAWN	CHECKED	APPROVED
12-27-88	0	DKM	NN	MJD

060495

SUPPORTING DATA FOR CROSS-SECTION A-A'



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- CI – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

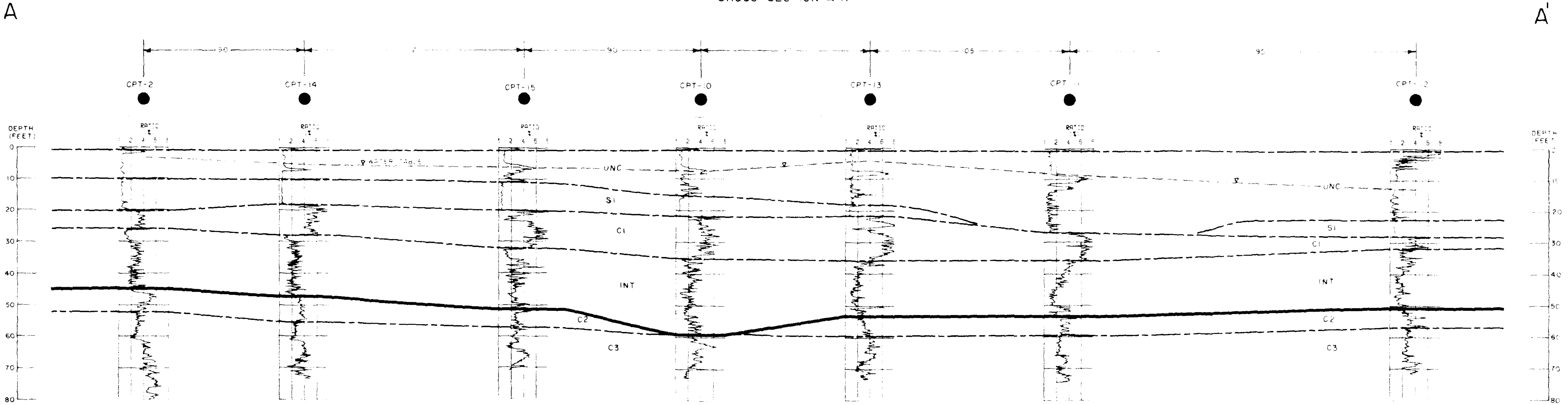
SUPPORTING DATA FOR CROSS-SECTION A-A'

(SEE PLATE 1 FOR LOCATION)

PROJECT NUMBER 26

039496

CROSS-SECTION A-A'



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI – SANDS, FINE TO MEDIUM GRAINED WITH SOME GRAVELS
- CI – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

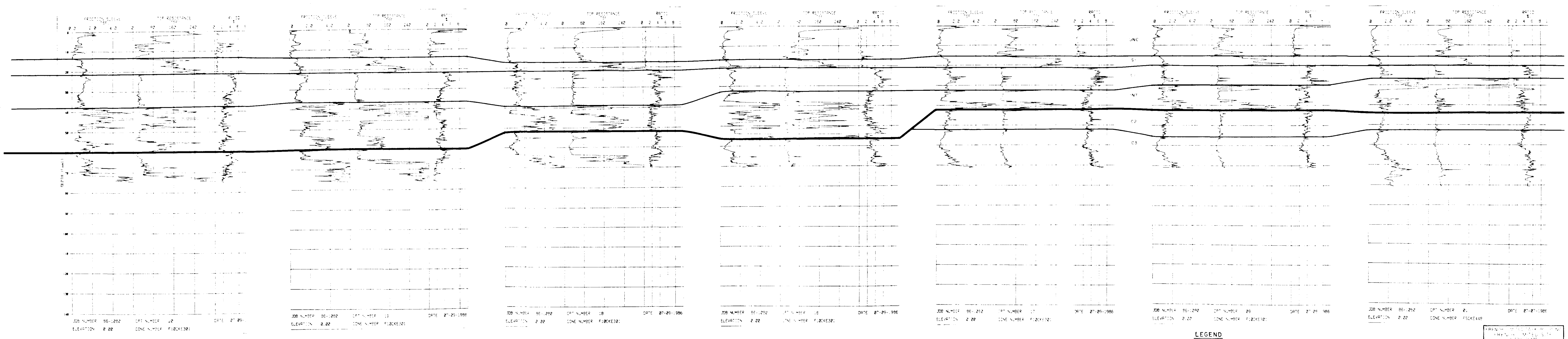
MIDDLE CLAYEY ZONE
- C2 – [illegible] CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

CROSS-SECTION A-A'

069497

B

SUPPORTING DATA FOR CROSS-SECTION B-B'



(CONTINUED ON NEXT SHEET)

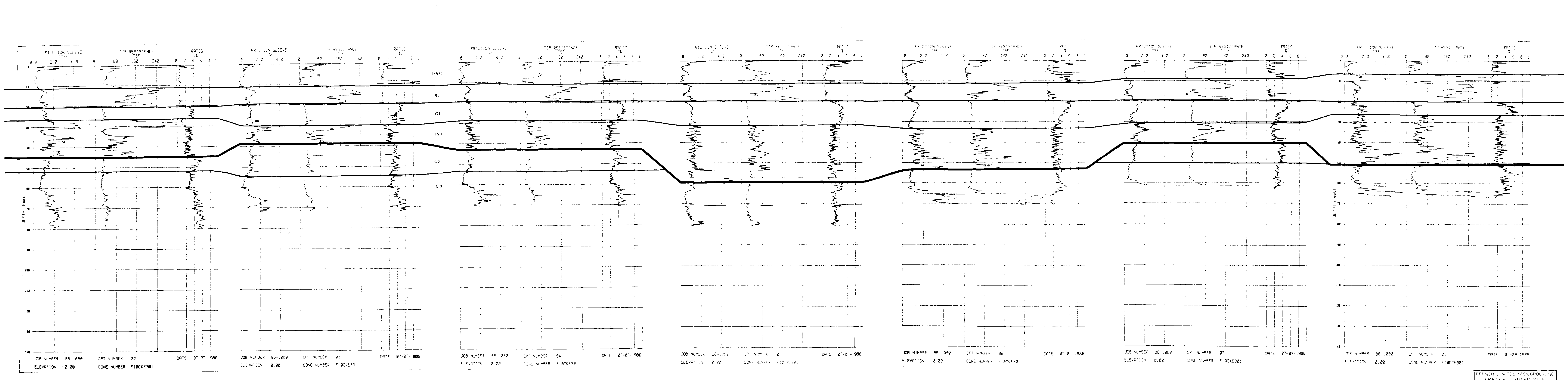
LEGEND

UPPER ALLUVIAL ZONE
- UNC - UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI - SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- CI - SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT - INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 - SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 - CLAYEY SILT AND SILTY CLAY

SUPPORTING DATA
FOR CROSS-SECTION
B-B'

060498



LEGEND

UPPER ALLUVIAL ZONE
- UNC - UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI - SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- CI - SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT - INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 - SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 - CLAYEY SILT AND SILTY CLAY

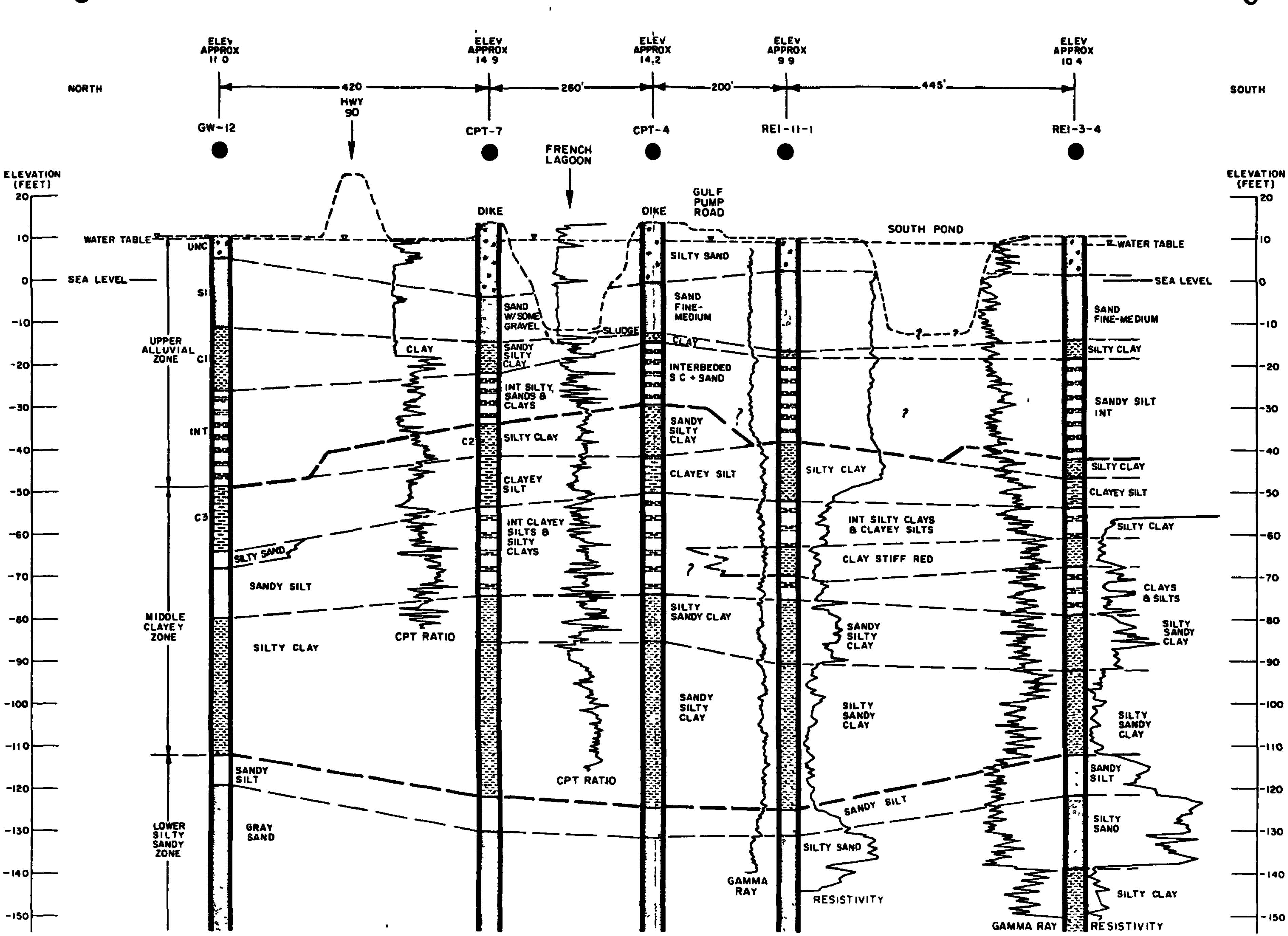
FRENCH LIMITED TASK GROUP, INC
FRENCH LIMITED SITE
CROSBY, TEXAS

SUPPORTING DATA FOR CROSS-SECTION B-B'

(SEE PLATE 1 FOR LOCATION)

PROJECT NUMBER 26

CROSS-SECTION C-C'



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI – SANDS, FINE TO MEDIUM GRAINED WITH SOME GRAVELS
- CI – SILTY CLAY, SILTY SANDY CLAY AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

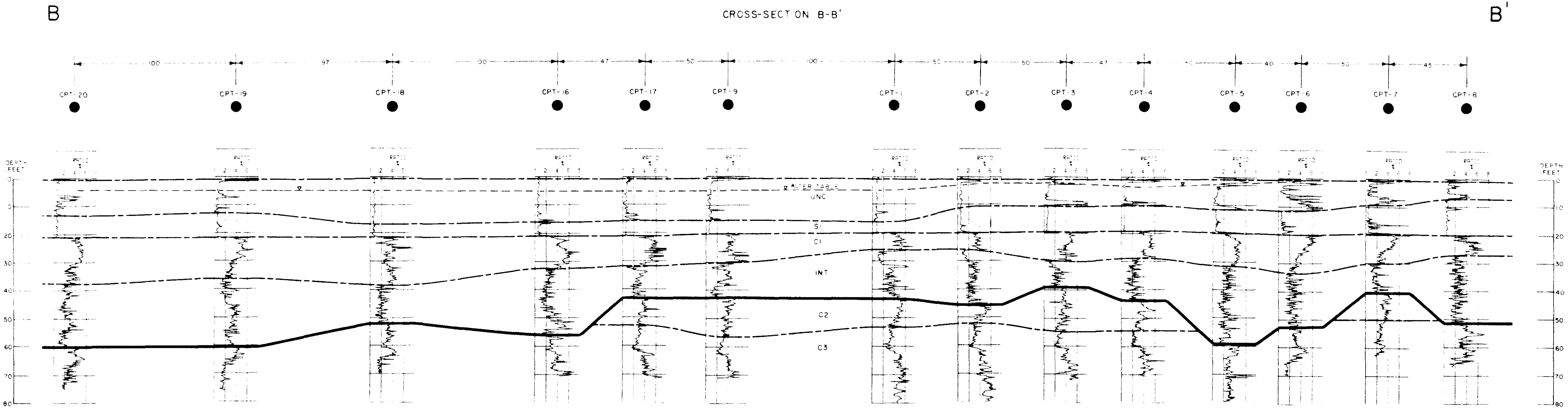
FRENCH LIMITED TASK GROUP, INC
FRENCH LIMITED SITE
CROSBY TEXAS

CROSS-SECTION C-C'

(SEE PLATE 1 FOR LOCATION)

PROJECT NUMBER 26

630499



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- S1 – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- C1 – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

CROSS-SECTION B-B'

SEE PLATE FOR LOCATION

PROJECT NUMBER

080501

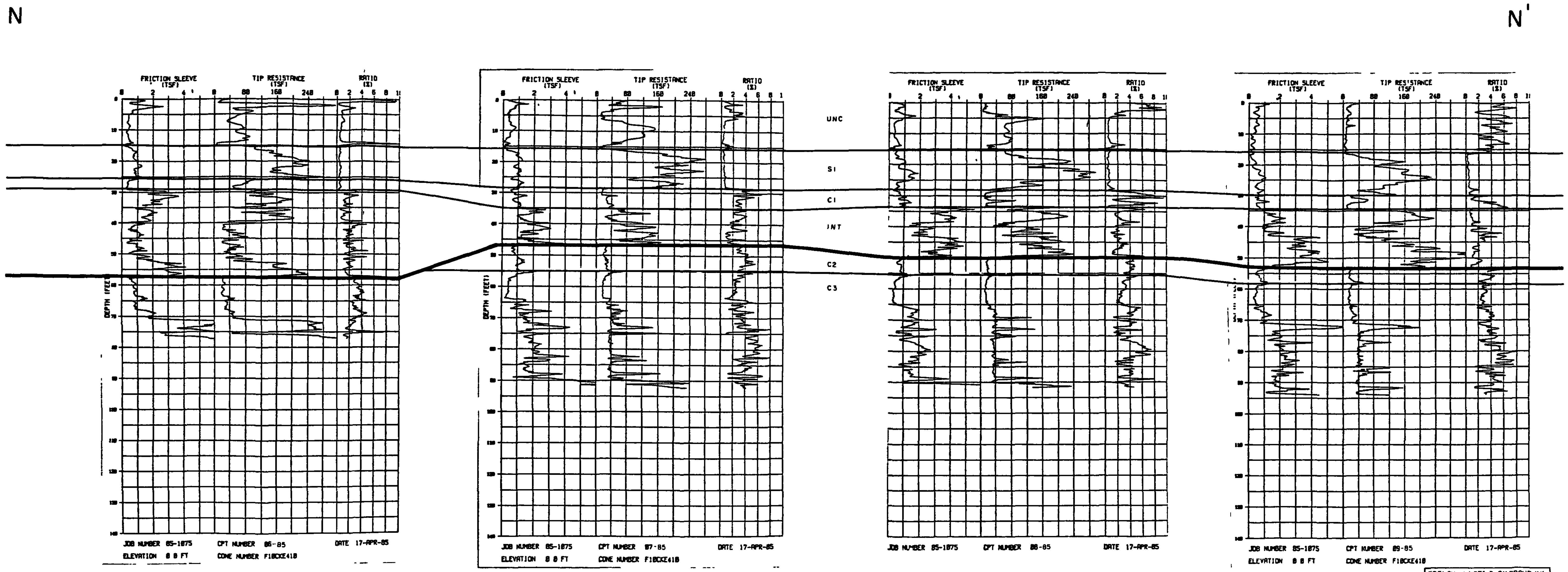
LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- S1 – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVEL
- C1 – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

CROSS-SECTION D-D'

069503



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL DEBRIS, AND LOOSE SILTY SANDS
- SI – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- CI – SILTY CLAY, SILTY SANDY CLAY AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

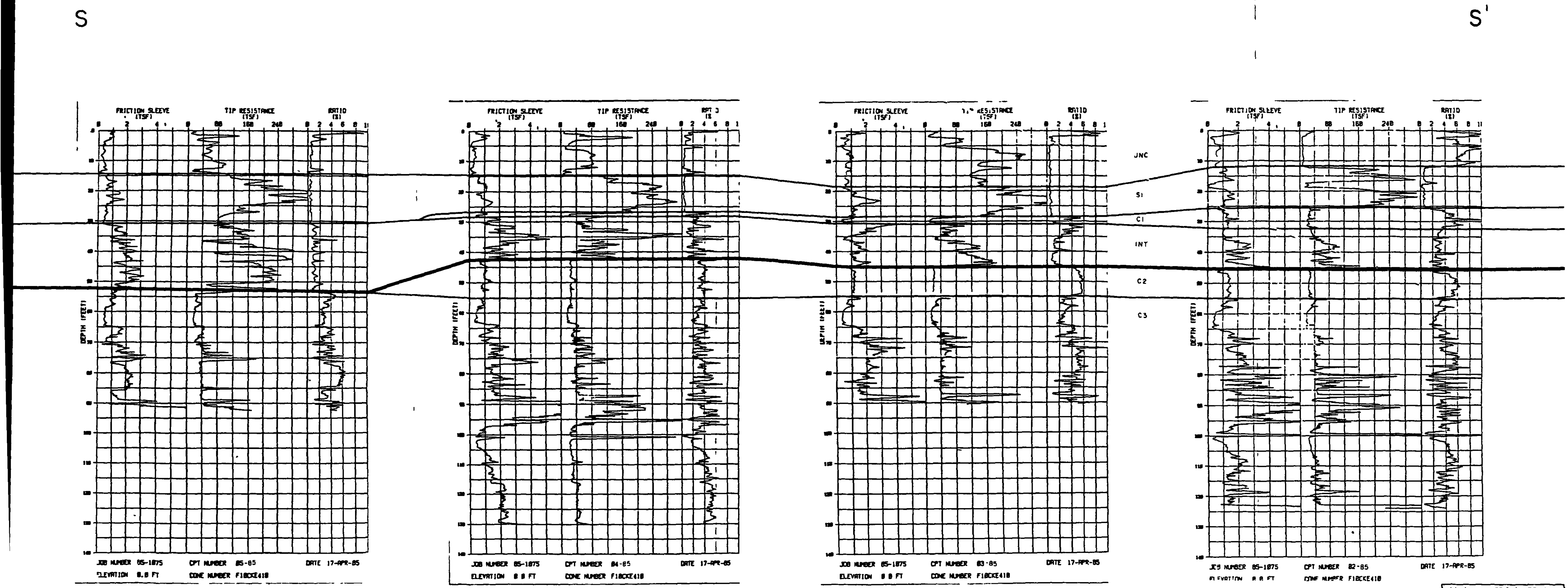
MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY SANDY SILTY CLAY AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

FRENCH LIMITED TASK GROUP, INC
FRENCH LIMITED SITE
CROSBY TEXAS

SUPPORTING DATA FOR FENCE DIAGRAM

(SEE P [illegible] FOR LOCATION)

PROJECT NUMBER 26



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL DEBRIS, AND LOOSE SILTY SANDS
- S1 – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- C1 – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

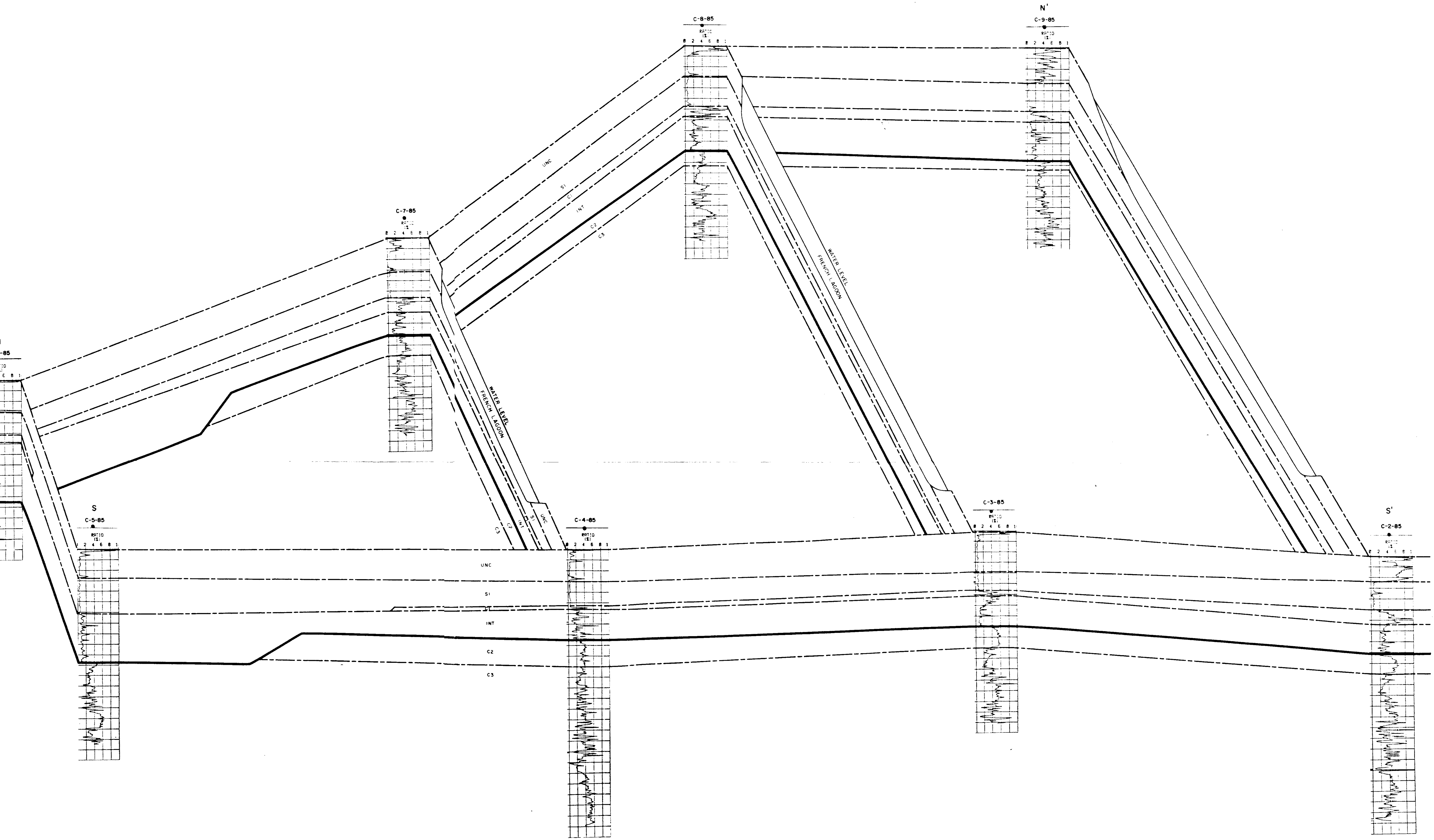
MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

FRENCH ED SITE

CROSBY

SUPPORTING DATA FOR FENCE DIAGRAM

502



LEGEND

UPPER ALLUVIAL ZONE
- UNC – UNCOMPACTED FILL, DEBRIS, AND LOOSE SILTY SANDS
- SI – SANDS, FINE TO MEDIUM GRAINED, WITH SOME GRAVELS
- CI – SILTY CLAY, SILTY SANDY CLAY, AND CLAY
- INT – INTERBEDDED SILTS, CLAYS, AND SANDS

MIDDLE CLAYEY ZONE
- C2 – SILTY CLAY, SANDY SILTY CLAY, AND CLAY
- C3 – CLAYEY SILT AND SILTY CLAY

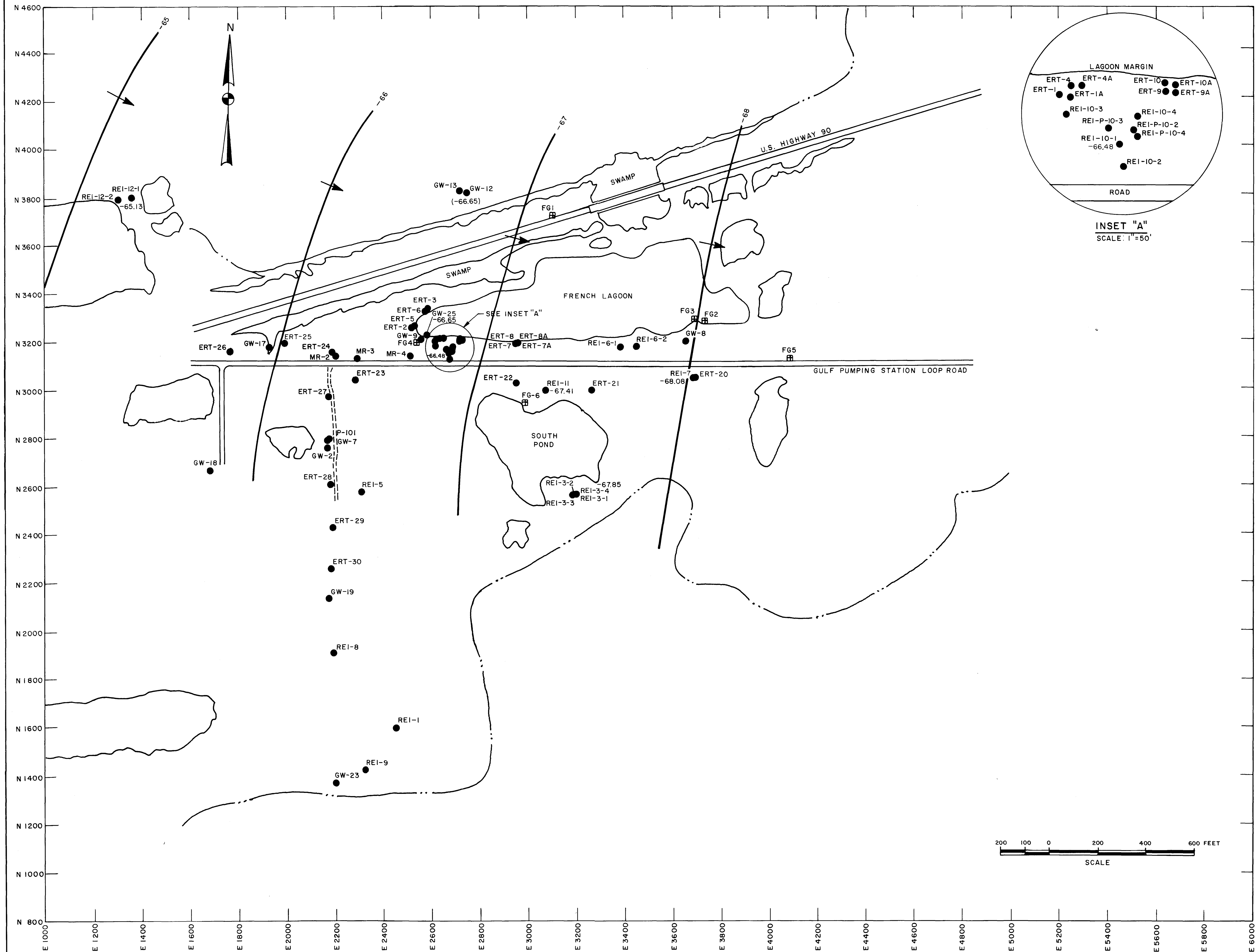
FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

FENCE DIAGRAM

(SEE PLATE I FOR LOCATION)

PROJECT NUMBER 26

060505



LEGEND

- FG1 ⊞ FLOOD GAUGE LOCATION
- GW-25 -66.65 ● WELL LOCATION WITH WATER LEVEL ELEVATION 8/19/86
- GW-12 (-66.65) ● WELL LOCATION WITH WATER LEVEL ELEVATION 3/10/86
- ⟶ GROUNDWATER FLOW DIRECTION
- —— -66 POTENTIOMETRIC SURFACE CONTOUR

NOTE: ELEVATIONS HAVE BEEN CORRECTED TO THE 1988 SITE SURVEY (ENSR, 1988b) EXCEPT FOR WELL GW-25 WHICH HAS BEEN PLUGGED AND ABANDONED

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

PLATE 2

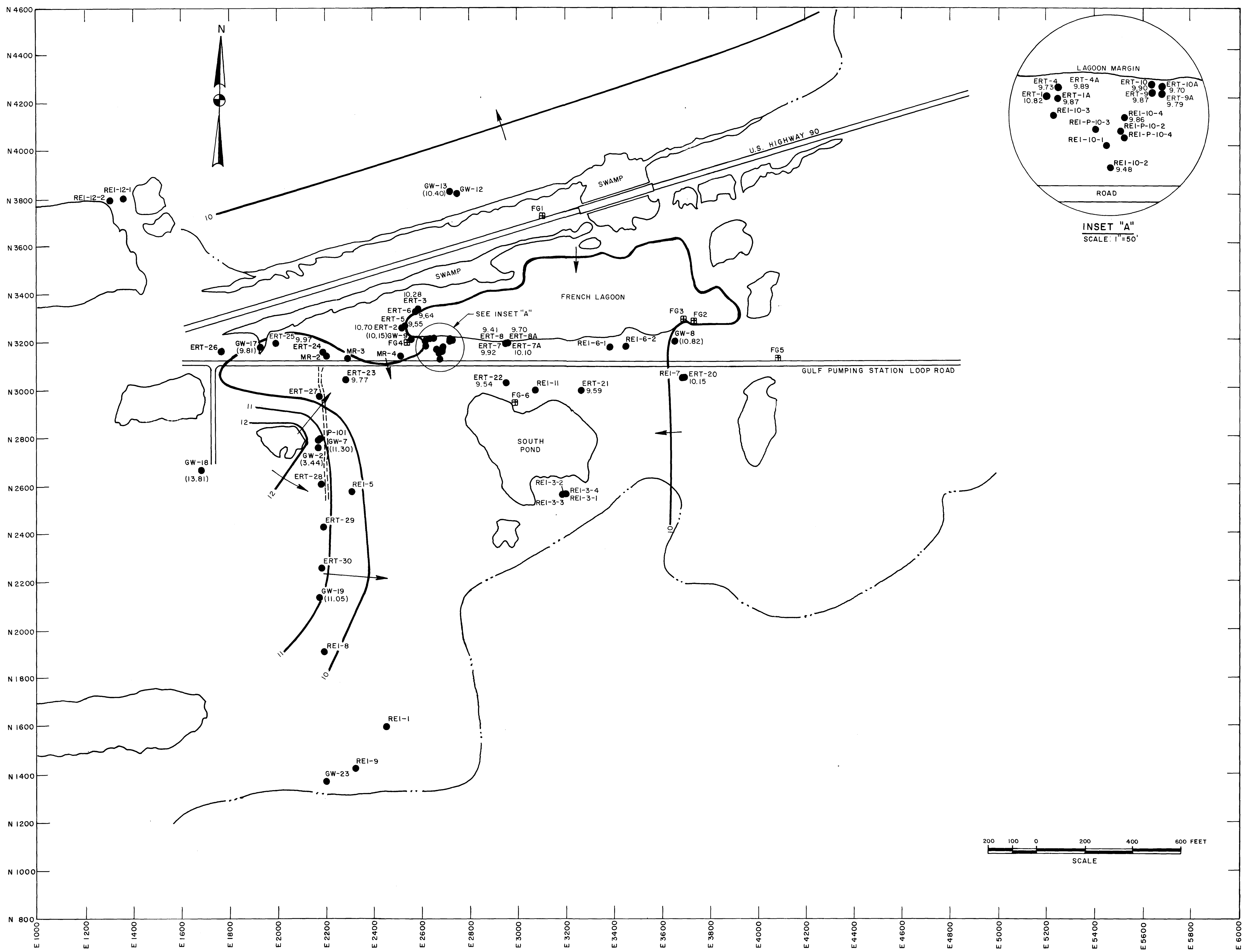
POTENTIOMETRIC SURFACE IN THE LOWER SILTY SAND ZONE

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-22-88	0	DKM	NN	MJD

060506



LEGEND

FG1 ⊞	FLOOD GAUGE LOCATION
GW-2 ●	WELL LOCATION
ERT-2 10.72 ●	MONITORING WELL LOCATION AND WATER LEVEL ELEVATION 3/3/88
GW-13 (10.40) ●	MONITORING WELL LOCATION AND WATER LEVEL ELEVATION 3/1/84
⟶	DIRECTION OF GROUNDWATER FLOW
10 ━━	POTENTIOMETRIC SURFACE CONTOUR

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

PLATE 3

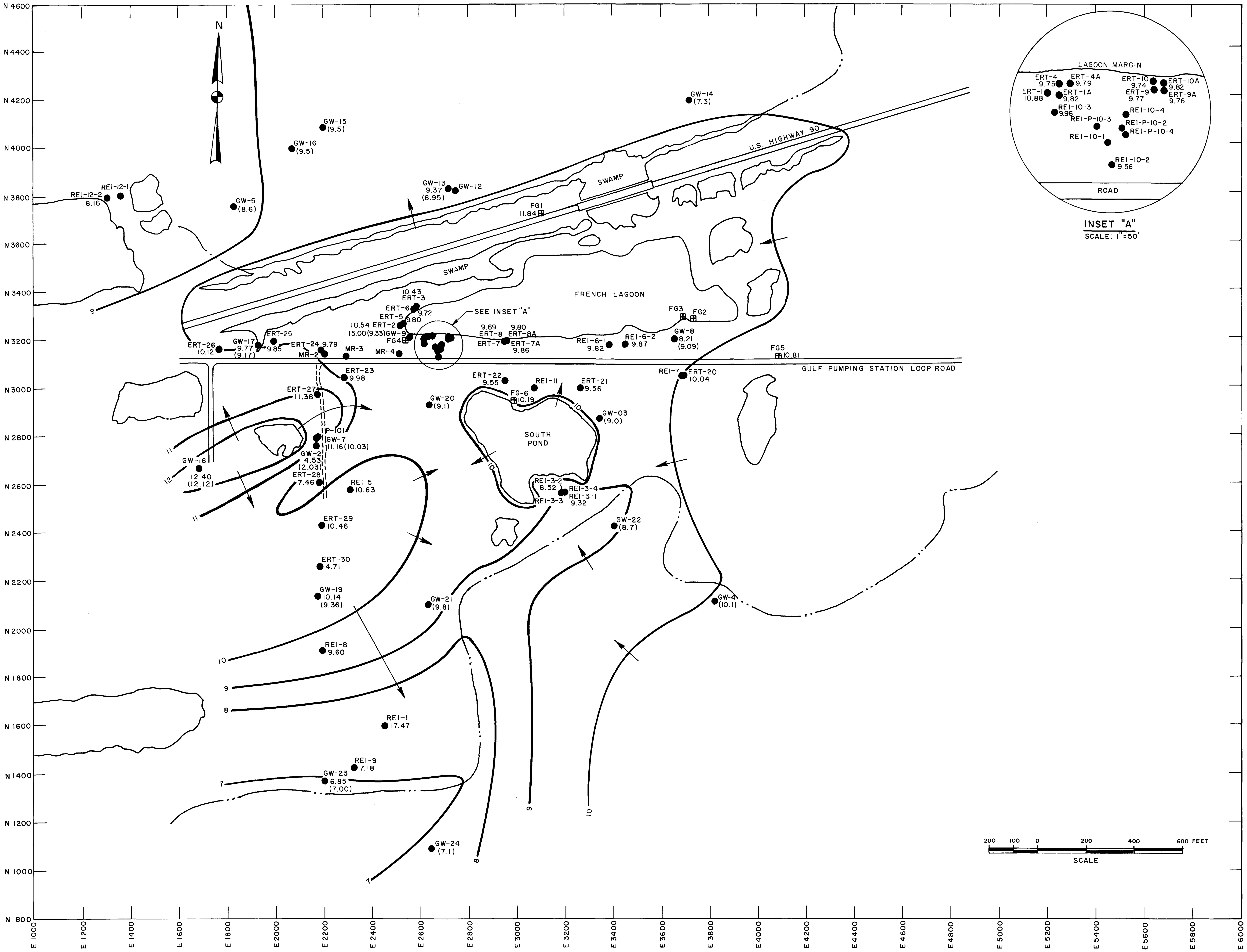
POTENTIOMETRIC SURFACE OF THE UPPER ALLUVIAL ZONE WINTER QUARTER

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-22-88	0	DKM	NN	MJD

080507



LEGEND

FG1 ⊞ FLOOD GAUGE LOCATION

GW-2 ● WELL LOCATION

ERT-2 10.54 ● MONITORING WELL LOCATION AND WATER LEVEL ELEVATION 4/11/88

GW-15 (9.5) ● MONITORING WELL LOCATION AND APPROXIMATE WATER LEVEL ELEVATION 5/17/84

FG1 ⊞ FLOOD GAUGE LOCATION

DIRECTION OF GROUNDWATER FLOW

10 POTENTIOMETRIC SURFACE CONTOUR

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.

FRENCH LIMITED SITE

CROSBY, TEXAS

PLATE 4

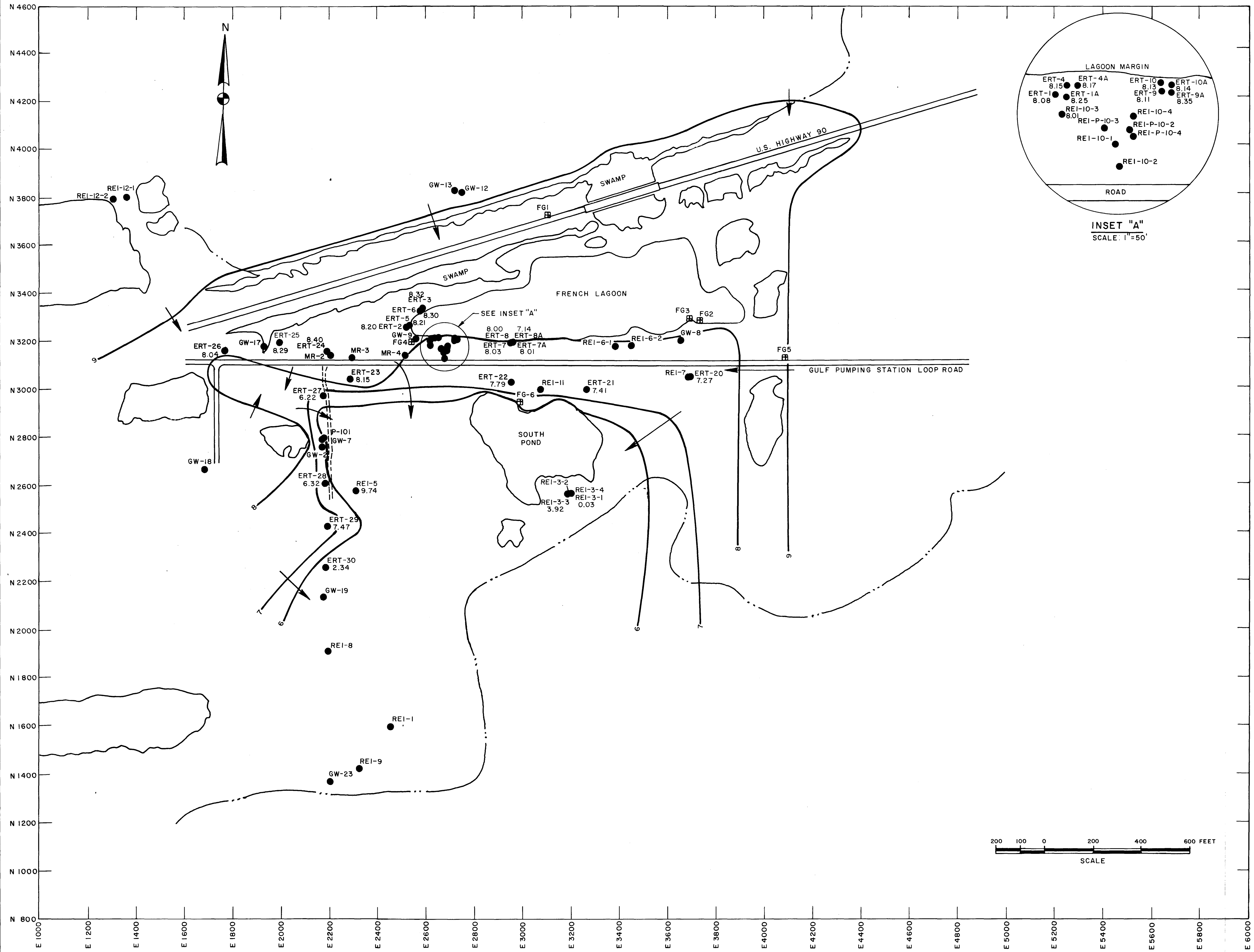
POTENTIOMETRIC SURFACE OF THE UPPER ALLUVIAL ZONE SPRING QUARTER

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-22-88	0	DKM	NN	MJD

069508



LEGEND

- FG1 ⊞ FLOOD GAUGE LOCATION
- GW-2 ● WELL LOCATION
- ERT-2 8.20 ● MONITORING WELL LOCATION AND WATER LEVEL ELEVATION 7/18/88
- ← DIRECTION OF GROUNDWATER FLOW
- 9 ── POTENTIOMETRIC SURFACE CONTOUR

WELL LOCATIONS ARE TAKEN FROM DRAWING No.007-001
MASTER MONITOR WELL LOCATION MAP
FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.

FRENCH LIMITED SITE

CROSBY, TEXAS

PLATE 5

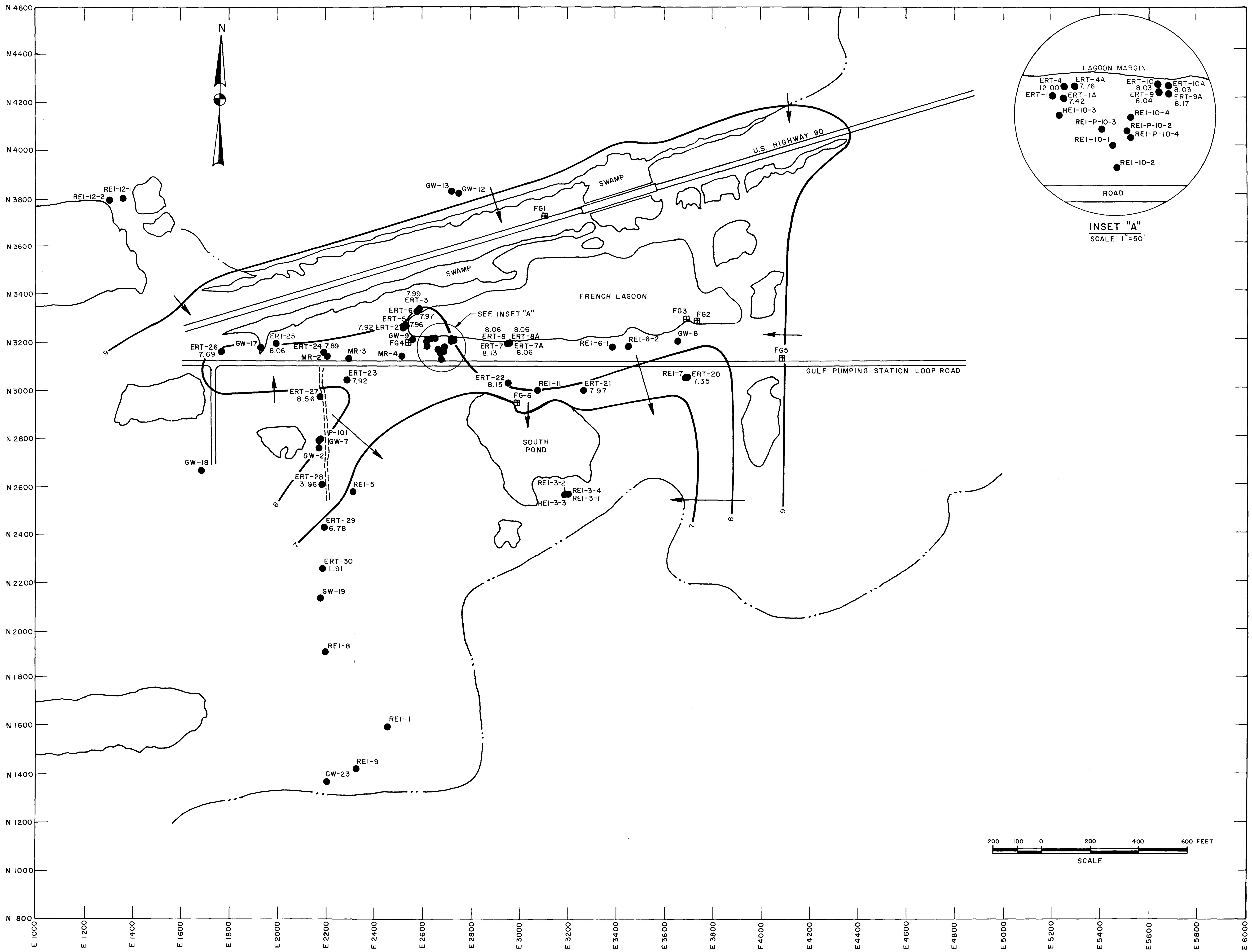
POTENTIOMETRIC SURFACE OF THE UPPER ALLUVIAL ZONE SUMMER QUARTER

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-23-88	0	DKM	NN	MJD

Applied Hydrology Associates, Inc.

030509



LEGEND

- FG1 — FLOOD GAUGE LOCATION
- GW-2 — WELL LOCATION
- ERT-2 7.92 — MONITORING WELL LOCATION AND WATER LEVEL ELEVATION 11/29/88
- DIRECTION OF GROUNDWATER FLOW
- 9 — POTENTIOMETRIC SURFACE CONTOUR

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.

FRENCH LIMITED SITE

CROSBY, TEXAS

PLATE 6

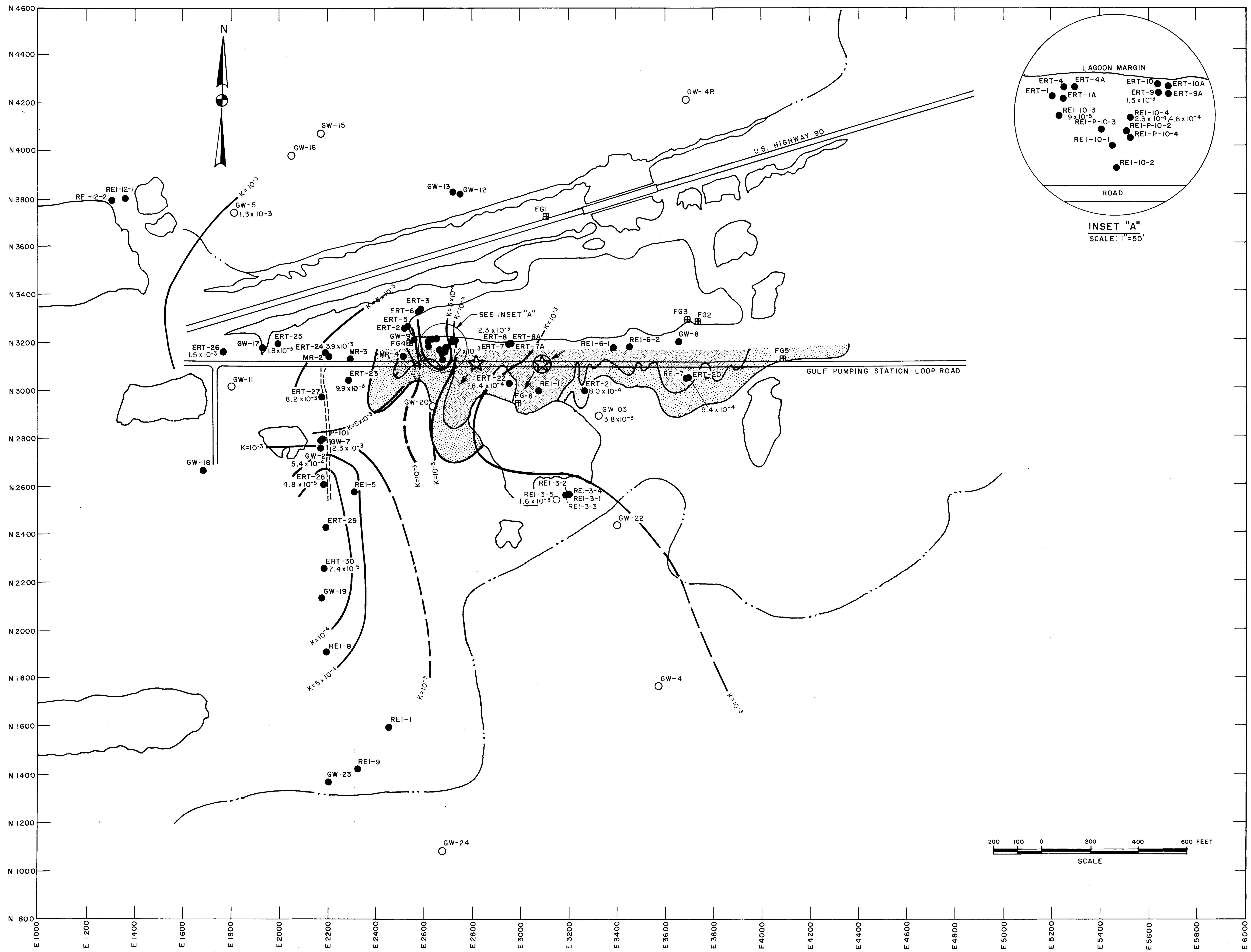
POTENTIOMETRIC SURFACE OF THE UPPER ALLUVIAL ZONE FALL QUARTER

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-23-88	0	DKM	NN	MJD

000510



LEGEND

- FG1 ⊞ FLOOD GAUGE LOCATION
- GW-2 ● WELL LOCATION
- ○ WELL LOCATION - NOT SURVEYED BUT TAKEN FROM THE SOIL VAPOR SURVEY, PLATE 1 (ENSR, 1988c)
- MINOR VAPOR LEVELS (1-10 VS)
- MODERATE VAPOR LEVELS (10-500 VS)
- ☆ HIGH VAPOR LEVELS (500-1000 VS)
- VERY HIGH VAPOR LEVELS (> 1000 VS)
- VS = VOLT-SECOND UNITS
- K = HYDRAULIC CONDUCTIVITY (CM/SEC)
- ⟵ POSSIBLE PATHWAY OF CONTAMINANT MIGRATION

● WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.

FRENCH LIMITED SITE

CROSBY, TEXAS

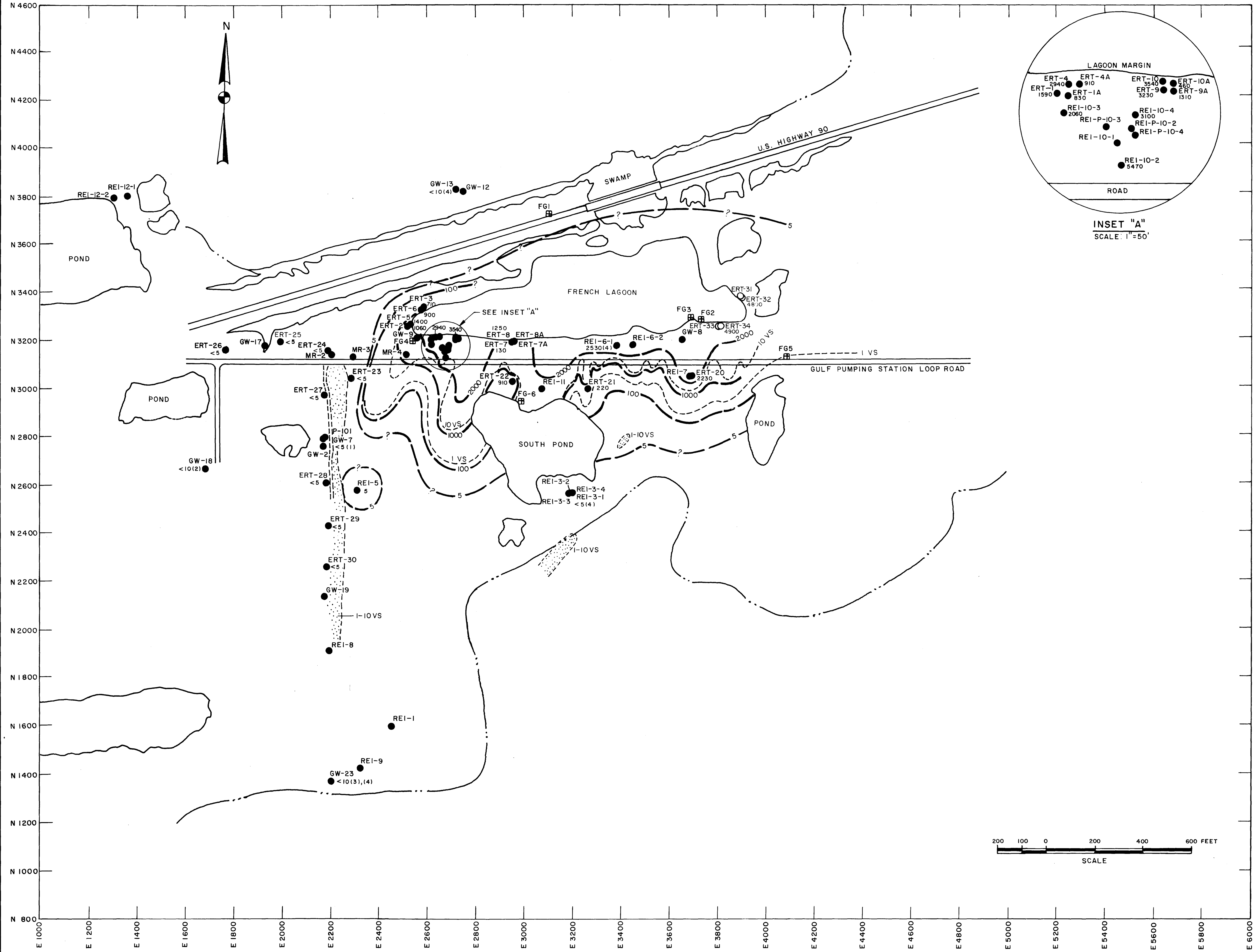
PLATE 7

ISOPLETHS OF AVERAGE HYDRAULIC CONDUCTIVITY COMPARED WITH SOIL VAPOR SURVEY RESULTS

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26				
DATE	REVISION	DRAWN	CHECKED	APPROVED
12-23-88	0	DKM	NN	MJD

069511



LEGEND

- FG1 ⊞ FLOOD GAUGE LOCATION
- ERT-2 1060 ● WELL LOCATION SHOWING UNWEIGHTED AVERAGE BENZENE CONCENTRATION (ug/L) IN UPPER ALLUVIAL ZONE GROUNDWATER ON SAMPLES TAKEN DURING 1988 (EXCEPT WHERE NOTED) SEE PLATE FOR DETAILS
- 2000 CONTOUR OF AVERAGE BENZENE CONCENTRATION (ug/L) IN UPPER ALLUVIAL ZONE GROUNDWATER

NOTES	SAMPLE DATES
(1)	Apr. 1983
(2)	Nov. 1983
(3)	Apr. 1984
(4)	July 1984

- 10VS ISOPLETH OF SOIL VAPOR CONCENTRATION (VOLT-SECOND UNITS) FROM ENSR (1988c)
- AREA OF LOW SOIL VAPOR CONCENTRATION (1-10VS) INTERPRETED AS NOT BEING RELATED TO GROUNDWATER CONTAMINATION

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.

FRENCH LIMITED SITE

CROSBY, TEXAS

PLATE 9

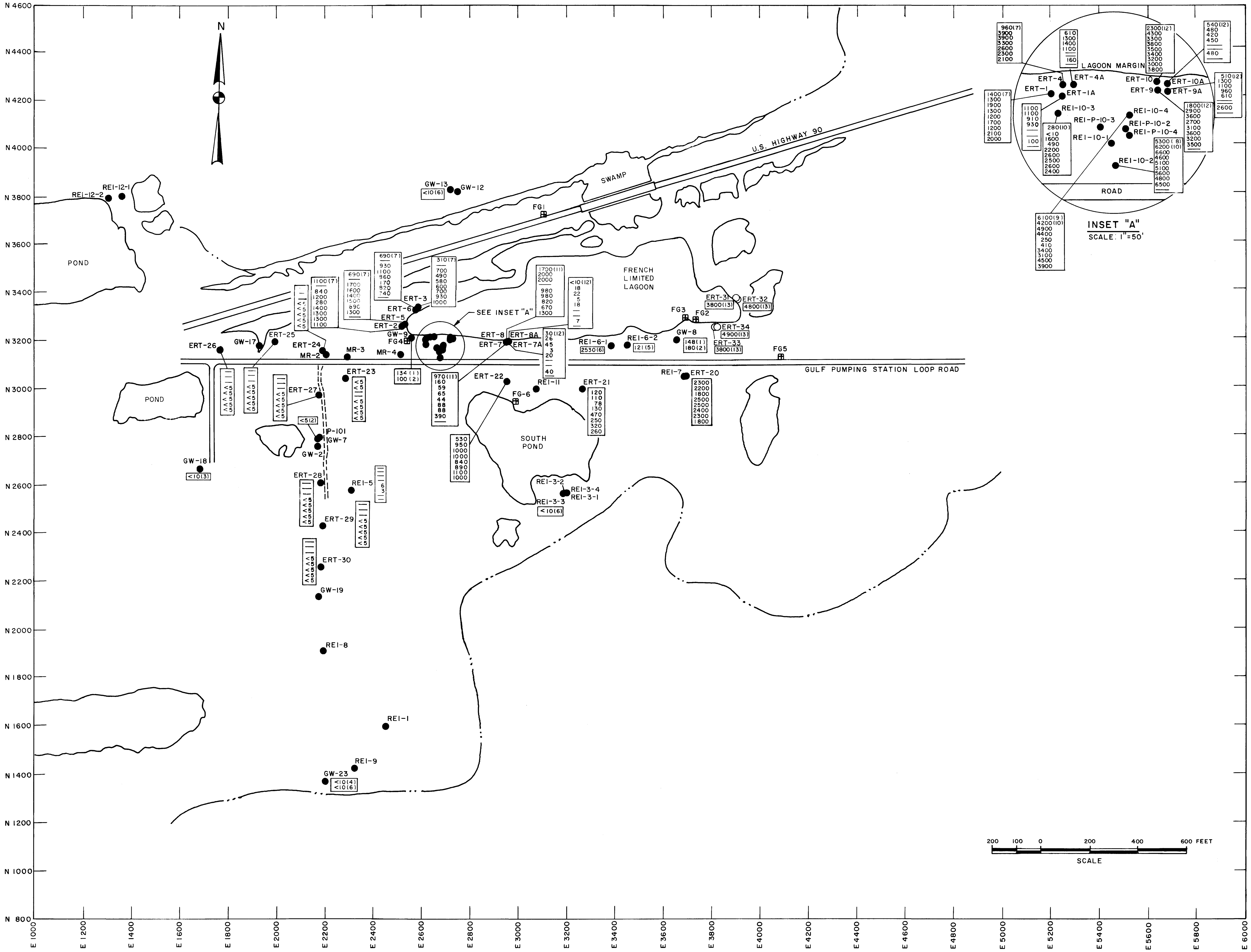
BENZENE CONCENTRATION (ug/L) IN UPPER ALLUVIAL ZONE GROUNDWATER DURING 1988

Applied Hydrology Associates, Inc.

PROJECT NUMBER: 26

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-29-88	0	DKM	MJD	NN

460512



LEGEND

FG1 ⊞ FLOOD GAUGE LOCATION

GW-2 ● WELL LOCATION (○ NOT SURVEYED)

BENZENE CONC. (ug/L) — SAMPLE DATE (UNLESS OTHERWISE NOTED)

1300	JAN 4,5,1988
1900	FEB 3-5,1988
1300	MAR 2-4,1988
1200	MAR 29 1988
1700	MAY 25,26,1988
1200	JUNE 22, 1988
2100	JULY 21, 1988
2000	OCT. 18, 1988

NOTES

(1) OCT. 1981
(2) APR. 1983
(3) NOV. 1983
(4) APR. 24, 1984
(5) JUL 3, 1984
(6) JUL 17, 1984
(7) APR 20, 1987
(8) AUG 31, 1987
(9) SEP 1, 1987
(10) SEP 27, 1987
(11) OCT. 6, 1987
(12) NOV. 20, 1987
(13) OCT. 18, 1988

WELL LOCATIONS ARE TAKEN FROM DRAWING No. 007-001 MASTER MONITOR WELL LOCATION MAP FRENCH LIMITED SITE (ENSR, 1988a)

DATUM: MEAN SEA LEVEL

FRENCH LIMITED TASK GROUP, INC.
FRENCH LIMITED SITE
CROSBY, TEXAS

PLATE 8
MEASURED BENZENE CONCENTRATIONS IN UPPER ALLUVIAL ZONE
1981 THROUGH 1988

PROJECT NUMBER: 26

Applied Hydrology Associates, Inc.

DATE	REVISION	DRAWN	CHECKED	APPROVED
12-29-88	0	DKM	MJD	NN